AD-A132 153 PROPELLANT COMBUSTION AND PROPULSION: NINE YEAR INDEX AND ABSTRACTS OF PU..(U) PRINCETON UNIV N J DEPT OF AEROSPACE AND MECHANICAL SCIENCES.. DEC 76 PUAMS-1321 1/2

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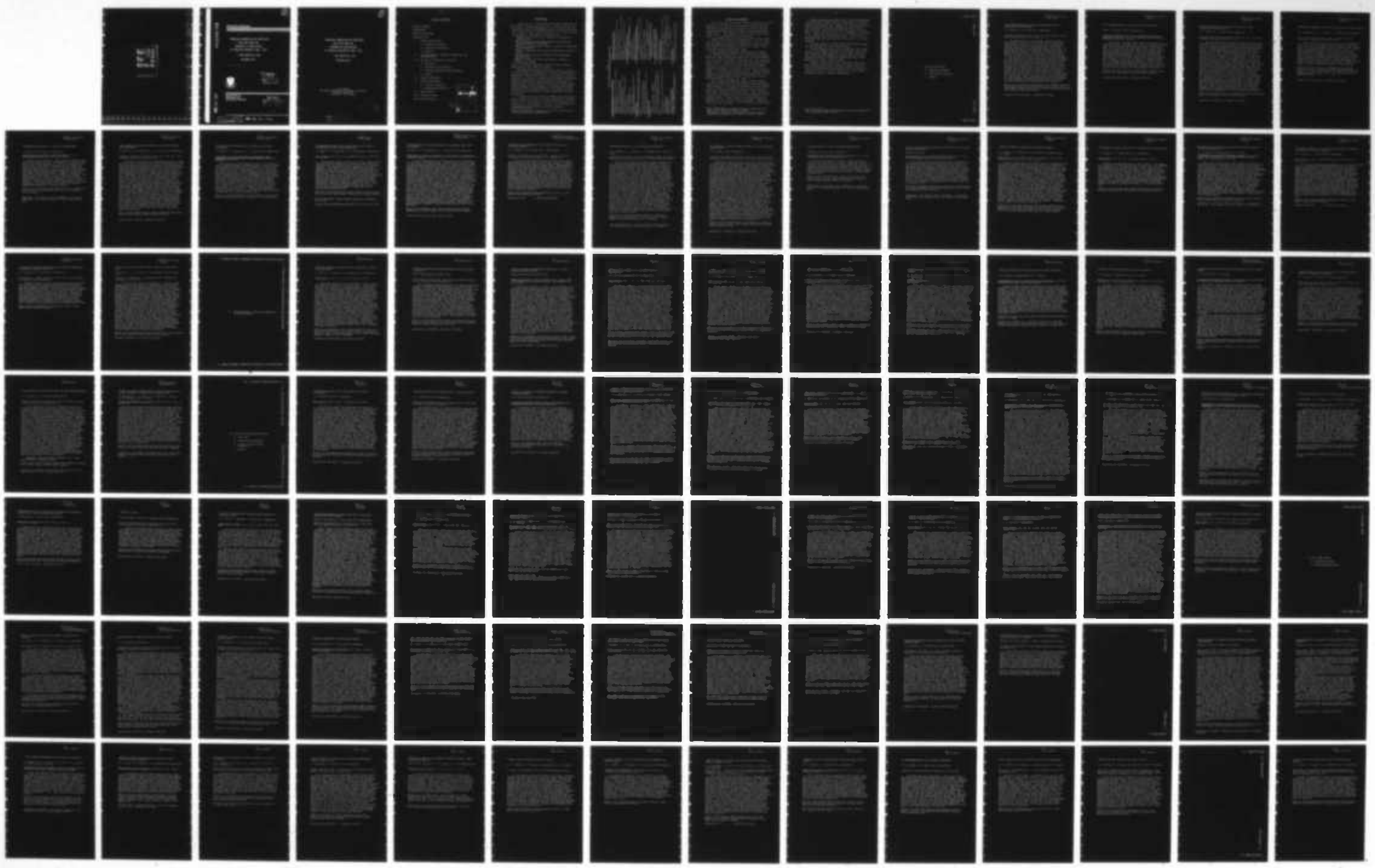

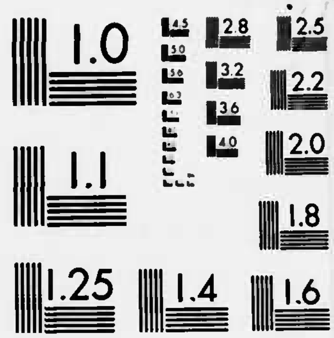

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PROPELLANT COMBUSTION AND PROPULSION: NINE YEAR INDEX AND ABSTRACTS OF PUBLICATIONS BY PRINCETON UNIVERSITY 1968 - 1976

PUAMS REPORT NO. 1321

DECEMBER 1976

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Department of Aerospace and Mechanical Sciences

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DECEMBER 1976

S. P. Group
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INTRODUCTION

During the nine year period that includes 1968 and 1976 the results of ~~much of our~~ research on solid propellant and propulsion related topics ~~were~~ are described in reports and technical papers.* These publications form a set of self-consistent sources on a wide range of topics ~~, e. g.~~, such as:

- Steady state burning (both composite and double base propellants);
- Unsteady burning (including combustion instability, extinguishment and ignition);
- Ignition of propellants and fuels (radiative, convective, and conductive);
- Porous propellants (ignition and steady state deflagration);
- Rocket Motors (ignition transients and performance predictions);
- Metal erosion (by thermal and chemical attack); and
- Combustion noise.

Thus for the benefit of other workers in these fields, we have prepared this index and summary.

The publications summarized in this document are the technical reports and papers which have been archived by the appropriate libraries and agencies. Some types of publications (i.e., preprints of papers later published in journals, progress reports which were superseded by final reports, administrative summary reports which merely summarize publications listed in this document, and informal presentation summaries) have not been included if the results reported in them are also contained in a more comprehensive archive publication.

It should be noted that the interplay among the publications is great since there has been a commonality of propellants, fuels, rocket motors, data reduction techniques, etc. throughout our investigations. Table 1 is an outline that indicates the scope of the various investigations.

*Several publications prepared in 1976 but with 1977 dates are also included for completeness.

TABLE 1

SCOPE OF PROPELLANT COMBUSTION AND PROPULSION INVESTIGATIONS

I. STEADY STATE BURNING MECHANISMS AND FLAME STRUCTURE

- AP Composite Propellants.
  - Experiments on spectral emitters, flame temperature distributions, surface heat release, etc.
  - Theoretical flame models and burning rate theory.
  - Prediction of particle size effects, (UFAP, etc.).
  - Application to nonsteady burning theory, i.e., extinction, ignition and combustion instability.
- Double Base Propellants - Similar experiments on flames.
  - Theory of Burning Rates.
  - Mechanism of Plateau Burning.
  - Application to nonsteady burning theory.
- Command Control of Burning Rate.
  - Theoretical study of effects of radiation, acoustic energy, perforated charges, pressure plate, etc.

II. NONSTEADY BURNING

- Experiments on extinction by depressurization, overshoot by sudden throttling, temperature effects on burning rate $r(p,T_0) \rightarrow r(p,q')$, etc.
- Theories:
  - Flame models: flame structure and nonsteady law.
  - Temperature sensitivity method (Soviet Theory).
- Applications - Extinction, thrust controllability, instability, ignition, internal ballistics, etc.

III. IGNITION MECHANISMS

- Experiments:
  - Conduction, Hot gas, reactive -- shock tube.
  - Convection, Hot gas, reactive -- shock tunnel.
  - Radiation -- Infrared by CO_2 laser and arc image furnaces.
  - Test Substances: Pure fuels (polymers), oxidizer crystals (HMX, AP, etc.), AP propellants, double base (e.g., N-5, M-9, etc.).
- Theories:
  - Transient flame models -- Surface reaction and gas phase reaction.
  - Zeldovich theory.
  - Ignition lag characteristics

IGNITION OF LIQUID FUELS

- Ignition wind tunnel.
- Thermally induced flow (liquid cell).

HYBRID ROCKET IGNITION AND COMBUSTION

- Experiments: ignition transient, reignition after shutdown, flame spreading, flame spectra, burning rate control, etc.

III. - Continued

FLAMMABILITY OF PROPELLANTS IN AIR (SAFETY)

- Theory of diffusion flame over self-flame.
- Experiments: Observe flame structures, measure temperature profiles and measure t_{ign} and p_{dl}.
- Propellants: NC types, HMX types, AP types.
- Special ingredients: Thermally stable binders, flame retardants, and coolants.
- Search for high ignition temperature propellants and self-extinguishing propellants.

IV. POROUS PROPELLANTS - HIGH SPEED BURNING

- Theory of forward flame propagation by convection.
  Two studies - (1) transient flame development and (2) steady state wave propagation.
- Processing of Porous Propellants.
- Experiments with granular propellant beds.

V. STARTING THRUST TRANSIENTS OF SOLID ROCKET ENGINES

- Objectives: Predictions of induction time, overshoot, thrust-time corridor, hangfire, etc.
- Theory includes ignition delay, flame spreading and gas dynamics during pressurization.
- AP propellants (aluminized and nonaluminized).
- Experiments: firing test with window motor.
- Special Objectives: Small A_p/A_t ratio motors, rapid ignition, reproducible ignition.

MICRO-ROCKET AND IMPULSIVE THRUSTER INTERNAL BALLISTICS

- Unconventional grain design.
- Application of high burn rate propellants.

VI. EROSION EFFECTS OF PROPELLANT COMBUSTION GASES

- Chemical attack vs thermal erosion of metals.
- Combustibility of metals and alloys.

VII. JET ENGINE NOISE SUPPRESSION

- Theory: Noise from various processes - internal and external.
- Adaptation of theory of nonsteady burning.
- Cold Flow Experiments: Acoustic measurements - $I(\phi,f,x)$, pressures, flow visualization, profiles.
- Combustion jet investigations: Mechanical suppression, decoupling experiments.
- Engine Experiments (in cooperation with others).

VIII. DROPLET BURNING

- Theory: Relate nonsteady response to steady state data.
- Application of theory to use with various power cycles.

SOURCES OF DOCUMENTS

All of the reports and papers that are summarized in this document are (or soon will be) available from the American Institute of Aeronautics and Astronautics (AIAA), National Technical Information Service (NTIS), Defense Documentation Center (DDC), the Chemical Propulsion Information Agency (CPIA), or the Engineering Societies Library.

Current AIAA papers are available for six months (after the meeting at which they are presented) at a cost of $2.00 from the American Institute of Aeronautics, Order Division, 1290 Avenue of the Americas, New York, N.Y. 10019. These should be ordered by AIAA Paper number.

AIAA accessioned documents (prefix A before number), [i.e., accessions announced in the International Aerospace Abstracts (IAA) Index*] are available at $5.00 per document up to a maximum of 20 pages. The charge for each additional page is $0.25. Microfiche of documents announced in IAA are available at the rate of $2.00 per microfiche on demand. Documents available in this manner are identified by the symbol # following the accession number. AIAA accessioned documents are available from the American Institute of Aeronautics and Astronautics, Technical Information Service, 750 Third Avenue, New York, N.Y. 10017.

NASA accessioned documents (prefix N before number) announced in NASA Scientific and Technical Aerospace Reports (STAR) Indexes** are generally available from the National Technical Information Service, Order Division, 5285 Port Royal Road, Springfield, Virginia 22161. Paper copy varies in price in accordance with the age of the document and the number of pages. In most cases a microfiche copy may be purchased for the price of $3.00 per document. Documents identified with the symbol # are available in this fashion.

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*IAA = International Aerospace Abstracts, published semimonthly with Cumulative Annual Indexes.
**NASA STAR = Scientific and Technical Aerospace Reports, published semimonthly with Cumulative Annual Indexes.

Defense Documentation Center (DDC) accessioned documents (prefix AD before number) which are announced in Government Reports Announcements (GRA) Indexes* are generally available from the National Technical Information Service (NTIS), Order Division, 5285 Port Royal Road, Springfield, Virginia 22161. Paper copy varies in price in accordance with the age of the document and the number of pages. In most cases, a microfiche copy may be purchased for the price of $3.00 per document.

Articles shown as a journal article may be most easily obtained through your local library system.

The Proceedings of the various Joint Army, Navy, NASA, and Air Force (JANNAF) meetings are available to qualified users from The Johns Hopkins University, Applied Physics Laboratory, Chemical Propulsion Information Agency, Johns Hopkins Road, Laurel, Maryland 20810.

Journal articles that are not available through your local library system and/or AIAA are generally available from the Engineering Societies Library (ESL), New York, N.Y. Photoprints cost 30 cents per page plus a $3.00 handling change per article. Postage is additional.

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*GRA = Government Reports Announcements, published semimonthly with Cumulative Annual Indexes.

I STEADY STATE

I. Steady State Burning

- A. Composite Propellant
- B. Double Base Propellant
- C. General

I STEADY STATE

I STEADY STATE

"THE BURNING MECHANISM OF AMMONIUM PERCHLORATE-BASED COMPOSITE SOLID PROPELLANTS"

J. A. Steinz, P. L. Stang and M. Summerfield

AIAA Paper No. 68-658, June 1968. New York: American Institute of Aeronautics and Astronautics.

The applicability of the granular diffusion flame model (GDF) and of the resulting theoretical burning rate law has been tested on a wide variety of AP propellants, most of them of standard formulations but some of non-standard formulation. A remarkable degree of agreement has been demonstrated for the standard formulations in the usual range of pressure (1-100 atm). Burning rate measurements were carried out at subatmospheric pressures also, all the way down to 0.01 atm, and here, too, the data are in line with the GDF theory, but with an extended version. In this extension, the overall gas phase flame is recognized as consisting of two stages, first the exothermic AP decomposition flame and then the fuel-oxidant diffusion flame. With various non-standard propellants, particularly those with small AP particle size, low AP loading and/or readily meltable fuel binders, plateau burning rate curves and, in extreme cases, intermediate pressure extinctions have been found. This behavior is caused by temporary localized extinctions of the flame and seems to be due to intermittent but wide-spread covering of the AP particles on the surface by a molten fuel layer. These findings on flame structure for both standard and non-standard propellants are important for understanding steady-state burning rates, non-steady burning (instability), extinguishment, and ignition.

Based on work performed under Contract Nonr 1858(32) sponsored by the Power Branch of the Office of Naval Research. This is the latest version of the 4th ICRRG Combustion Conference paper (X68-16019#) by the same authors.

Accession No. A68-33841# - Available from AIAA.

"LOW PRESSURE BURNING OF COMPOSITE SOLID PROPELLANTS"

Johan A. Steinz and Martin Summerfield

Advances in Chemistry, Vol. 88, Propellants Manufacture, Hazards and Testing, Jan. 1969, American Chemical Society, Washington, D.C., pp. 244-295.

The granular diffusion flame theory is quantitatively valid for various AP propellants in the rocket pressure range 1-100 atm and in good qualitative agreement with burning data at low pressures (to 0.05 atm). The complete theory must include the pressure dependence of the kinetic rate of the first stage of the flame - i.e., the exothermic redox reaction between the gases produced by the dissociative sublimation of the solid AP. It is shown theoretically that above 10 atm this first stage can be treated as having zero thickness, and one can disregard its pressure dependence. Generally, burning rate strands extinguish below 0.1 atm, apparently because unreacted AP escapes from the flame zone, and because convective cooling of the flame at the strand edges becomes dominant; radiation losses are not strong enough to account for the observed extinctions.

Based on work performed under contract Nonr 1858(32) sponsored by the Power Branch, Office of Naval Research.

Accession No. A70-19914 - Available from AIAA.

"THE BURNING MECHANISM OF AMMONIUM PERCHLORATE-BASED COMPOSITE SOLID PROPELLANTS"

J. A. Steinz, P. L. Stang and M. Summerfield

Aerospace and Mechanical Sciences Report No. 830, Feb. 1969, Princeton University, Princeton, N.J.

The applicability of the granular diffusion flame model (GDF) and of the resulting theoretical burning rate equation has been tested on a wide variety of AP propellants, most of them of standard formulation but some of non-standard formulation. A remarkable degree of agreement has been demonstrated for the standard formulations in the usual range of pressure (1-100 atm). Burning rate measurements were carried out at subatmospheric pressures also, all the way down to 0.01 atm, and here, too, the data are in line with the GDF theory, but with an extended version. In this extension, the overall gas phase flame is recognized as consisting of two stages, first the exothermic AP decomposition flame and then the fuel-oxidant diffusion flame. With various non-standard propellants, particularly those with small AP particle size, low AP loading and/or readily meltable fuel binders, plateau burning rate curves and, in extreme cases, intermediate pressure extinctions (20-70 atm) have been found. This behavior is caused by temporary localized extinctions of the flame and seems to be due to intermittent but widespread covering of the AP particles on the surface by a molten fuel layer. The melting fuel is important also in determining extinction at low pressure ($\lesssim$ 1 atm). Combustion inefficiency and convective cooling by the ambient gases are the main causes of low pressure extinction (0.1-0.01 atm) for strands of propellants with a dry (charred) burning surface. These findings on flame structure are important for understanding steady state burning rates, non-steady burning (instability), extinguishment, and ignition.

Based on work performed under contract Nonr 1858(32) sponsored by the Power Branch, Office of Naval Research.

Accession No. AD688944 - Available from NTIS.

"COMBUSTION MECHANISMS OF FUEL RICH PROPELLANTS IN FLOW FIELDS"

C. A. Saderholm, R. A. Biddle, L. H. Caveny and M. Summerfield

AIAA Paper No. 72-1145, Nov. 1972. New York: American Institute of Aeronautics and Astronautics.

Combustion characteristics of fuel-rich AP propellants that burn only when exposed to flowing gases ($\sim$1500K and 10 to 60 atm), and extinguish when flow stagnates were investigated. Photographs indicate that cross-flow over the propellant surface causes the O/F flame to come closer to the burning surface, probably by turbulent mixing, thereby intensifying heat feedback from the flame to the surface. When cross-flow is stopped, extinguishment occurs, evidently because mixing is reduced to where heat feedback from the flame does not sustain combustion. These phenomena are modeled by direct extensions to the granular diffusion flame theory. Theoretical pressure and Mach number effects on burning rate ($r \sim p^{1/6}(MP)^{3/8}$) agree with firing data.

A portion of this effort was supported by the Lockheed Missiles and Space Company, Inc. under subcontract No. 17-10879 of U.S. Navy Prime contract No. N00030-71-C-0142 and subcontract No. 17-10962 of U.S. Navy Prime contract No. N00030-72-C-0102.

Accession No. A73-14915# - Available from AIAA.

"TEMPERATURE SENSITIVITY OF DOUBLE BASE PROPELLANTS"

N. Kubota, L. H. Caveny, M. Summerfield

Proceedings of 8th JANNAF Combustion Meeting, Vol. 1, CPIA Publication 220, Nov. 1971, pp. 387-401.

Studies were directed at understanding the physical and chemical processes that are influenced by the initial temperature of double base propellants. Burning rate data were obtained over a wide range of pressure (0.5 to 100 atm) and initial temperature (240 - 350 K) for several double base propellant types (NC/NG cast propellants with carbon and KNO_3 additives; the standard N-5 plateau propellant; plastisol NC with TMETN; platonized NC/TMETM). Diagnostic experiments revealed the gross features of the combustion processes. The consistency of the burning rate data, combustion limits, thermal properties, et al was examined in terms of Zeldovich-Novozhilov stability criteria. Calculated results from a solution to a premixed laminar flame representing the gaseous reactions at the propellant surface agreed with measured temperature sensitivity of burning rate data.

Based on work performed under sponsorship by the Power Branch of the Office of Naval Research and by the Army Research Office (Durham).

Accession No. for entire volume - AD890819L - Distribution Controlled - Not Available from DDC - Available only from CPIA.

"THE MECHANISM OF SUPER-RATE BURNING OF CATALYZED DOUBLE BASE PROPELLANTS"

N. Kubota, T. J. Ohlemiller, L. H. Caveny and M. Summerfield

Aerospace and Mechanical Science Report No. 1087, Mar. 1973, Princeton University, Princeton, N.J.

This study is directed at understanding how organic lead salts (at the 1% level) alter the burning mechanisms of double base propellants to produce large (up to 300%) burning rate increases (super-rate burning) and domains of reduced burning rate pressure and temperature sensitivity (plateau burning). Investigations were carried out with nitrocellulose and trimethylolethane trinitrate (TMETN) double base propellants with systematic variations in additives (including lead powder, lead oxide, lead salicylate, copper powder, copper salicylate, finely divided carbon, and oxamide), particle size, and degree of dispersion. Diagnostic experiments (from 0.1 to 100 atm) examined burning rate behavior, gas-phase structure, burning-surface structure, temperature profiles in the reaction zones, and global effects. The micro-thermocouple experiments revealed that 1% lead salts have less than a 10% effect on surface temperature and surface heat release but produce significant increases (70 to 100%) in the fizz zone temperature gradients. Lead salts decompose and directly affect the surface reaction layer ($\sim 20\mu$ thick at 20 atm). The lead salts' decomposition products react with the nitrate esters to produce an increased amount of solid carbon. The portion of decomposed organic molecules which appears at the surface in the form of carbon rather than readily oxidizable aldehydes reduce the effective fuel to oxidizer ratio (aldehyde to NO_2) and, thus, shifts the equivalence ratio toward the stoichiometric value; this accelerates the reaction rates in fizz zone and produces super rate burning.

Based on work performed under Contract N00014-67-A-0151-0023 from the Power Branch, Office of Naval Research.

Accession No. AD763786 - Available from NTIS.

"THE BURNING RATE FLEXIBILITY OF PLASTISOL DOUBLE BASE PROPELLANTS"

N. Kubota, T. J. Ohlemiller, L. H. Caveny and M. Summerfield

Proceedings of Tenth International Symposium on Space Technology and Science, Tokyo, Japan, September 1973, pp. 135-147.

The burning rate and pressure exponent of an important class of moderate energy propellants (I_{sp} = 236 sec at standard reference conditions) can be varied by as much as 400% by the addition of small percentages (< 2%) of lead salts and copper salts (e.g., lead salicylate, lead 2-ethylhexoate, and cupric salicylate). These propellants are slurry cast, filled nitrocellulose (NC) and trimethylolethane trinitrate (MTN) plastisols manufactured in conventional vertical mixers. They have the important advantage of being less hazardous and easier to manufacture than the NC and nitroglycerin propellants manufactured by extrusion processes. Experimental results show how the burning rate can be controlled (e.g., from 0.25 to 1.0 cm/sec at 20 atm and from 0.9 to 1.4 cm/sec at 100 atm) and how domains of reduced burning rate pressure sensitivity (i.e., burning rate exponents between -0.1 and 0.1 between 60 and 120 atm) can be produced by the addition of lead and copper salts.

Based on work performed under contract N00014-67-A-0151-0023 issued by the Power Branch of the Office of Naval Research.

AN EXPERIMENTAL STUDY OF THE SITE AND MODE OF ACTION OF PLATONIZERS IN DOUBLE BASE PROPELLANTS

N. Kubota, T. J. Ohlemiller, L. H. Caveny and M. Summerfield

AIAA Journal, Vol. 12, No. 12, December 1974, pp. 1709-1714.

Certain metal organic salts (e.g., lead or copper salicylate) when used in double base propellants induce desirable insensitivities of burning rate to pressure and initial temperature. To understand this, the combustion wave zones (luminous flame, dark, fizz, and surface reaction zones) were examined by means of photography and fine thermocouples (4 micron bead). The metal salts significantly alter the surface and fizz zones. The surface zone accumulates carbonaceous material coincident with the appearance of an accelerated burning rate in the catalyzed case. No attendant change in surface heat release is detected. Coinciding with this carbonaceous layer occurrence are substantial (50 to 100%) increases in conductive feedback from the fizz zone. This latter effect is believed directly responsible for the altered burning behavior though its origin may lie in the altered surface chemistry.

Based on work performed under contract N00014-67-A-0151-0023 sponsored by the Power Branch of the Office of Naval Research.

Not yet cataloged - Can be ordered from AIAA as AIAA Paper No. 74-124.

Journal article supersedes AIAA Paper No. 74-124, Jan. 1974.

"THE MECHANISM OF SUPER-RATE BURNING OF CATALYZED DOUBLE BASE PROPELLANTS."

N. Kubota, T. J. Ohlemiller, L. H. Caveny and M. Summerfield

Proceedings of Fifteenth Symposium (International) on Combustion, 1974, pp. 529-537.

Previous investigators have offered qualitative explanations for the large, pressure-dependent, burning behavior changes seen in nitrate ester propellants when lead or copper salts are added. The most developed qualitative models are those of Camp and of Powling and coworkers but both exhibit certain discrepancies with experiment. New evidence reported here derives from radiation-assisted burning tests in which the spectral content (particularly ultraviolet) of the impinging radiation was varied; contrary to the original hypothesis of Camp, the UV component of the radiation yielded no special burning rate enhancing effect. Experimental evidence recently presented by the authors shows that the burning rate enhancement by lead or copper compounds is a result of acceleration of the fizz zone reactions; this is accompanied by an increased production of carbonaceous material at the burning surface. Therefore it is hypothesized that the acceleration is due to a shift in equivalence ratio toward the stoichiometric when potentially burnable fuel molecules are instead carried through the fizz zone as solid carbon. A simplified mathematical model of this hypothesis is developed based on representing the equivalence ratio change as a shift from a single normal reaction pathway toward a second, more reactive pathway. This hypothesis successfully explains the appearance of a region of enhanced burning rate and its disappearance at higher pressures but it is shown that sudden disappearance (mesa burning), sometimes seen experimentally, requires a further mechanism whose nature is not yet clear.

Based on work performed under Contract N00014-67-A-0151-0023 sponsored by the Power Branch of the Office of Naval Research.

Available through your local library system.

"BURNING RATE MEASUREMENT OF THIN SHEETS OF DOUBLE BASE PROPELLANT (HEN-12)"

L. H. Caveny, C. R. Felsheim and M. Summerfield

Aerospace and Mechanical Sciences Dept., Report No. 1301, Princeton University, Princeton, N.J., October 1975

The special problems associated with determining strand burning rates of very thin (0.040 inches) sheets of an NC/NG double base propellant (specifically HEN-12) were assessed and the accuracies of several strand burning experiments were evaluated. Strand burning experiments were carried out in several media over a range of temperatures (20 to 140 F) and pressures (500 to 1500 psi): nonflowing N_2, N_2 flowing parallel to flame, water, and oil. Except for oil, all media produced consistent burning rate data. However, burning in nonflowing N_2 minimized the heat loss effects. High speed photographs and extinguished specimens showed the extent that the media retarded the burning rate of the very thin strands. Error analyses indicated that the strand burning method of using nonflowing N_2 and conventional breakwire timing of the burning period can be refined to produce errors of less than 0.5% and that the largest source of error is the determination of breakwire position.

Based on work performed under sponsorship of the U.S. Army under Contract DAA21-74-C-0332.

Accession No. AD . Available from NTIS.

"THEORETICAL STUDIES OF DIFFUSION FLAME STRUCTURES"

C. H. Waldman, S. I. Cheng, W. A. Sirignano and M. Summerfield

Aerospace and Mechanical Sciences Report No. 860, Jan. 1969, Princeton University, Princeton, N.J. (Also AFOSR 69-0350 TR)

Two problems concerning diffusion flames characterized by a coordinate-dependent Damkohler number were studied theoretically, namely the structure of diffusion flames in laminar boundary layers and the one-dimensional unsteady ignition of solid fuels. The model selected for the study of the structure of diffusion flames in laminar boundary layers consists of an oxidant-containing flow over a wedge of condensed fuel. The fuel was assumed to undergo equilibrium vaporization and the chemical reaction was represented by Arrhenius kinetics of arbitrary order. It was shown that in general the boundary layer exhibits a continuous spectrum of burning from frozen to equilibrium owing to the dependence of the Damkohler number on the downstream coordinate. The near-equilibrium regime was analyzed by the method of matched asymptotic expansions. The model for the study of the unsteady ignition of solid fuels consisted of a solid fuel suddenly exposed to hot oxidizing gas. The chemical reaction was represented by second-order Arrhenius kinetics. It was shown that the important dimensionless parameter in this problem is the Damkohler number divided by the Peclet number squared. Perturbation analysis (for small time) was carried out for cases neglecting and including convective effects by the integral and perturbation series methods respectively. The convective effects were shown to be negligible in that both analyses gave similar predictions for the ignition delay time. The ignition criterion employed was based on the equality of heat generation due to chemical reaction and the heat loss by conduction at the solid surface.

Based on work performed under Contract AF 49(638)1267 sponsored by the Air Force Office of Scientific Research, Office of Aerospace Research, U.S. Air Force.

Not Cataloged by DDC - available from Interlibrary Loans, Princeton University Library, Princeton, N.J. 08540.

"A FEASIBILITY STUDY OF COMMAND CONTROL OF SOLID PROPELLANT BURNING RATE"

L. H. Caveny and M. Summerfield

Aerospace and Mechanical Science Report No. 893, Feb. 1970, Princeton University, Princeton, N.J. Also AFRPL TR-69-249.

Analytical studies of twenty methods of command control of burning rate were performed to help establish which methods are most likely to be effective. Any method which offers a ±5% or greater throttleability is of interest. Since the study was not directed at a particular application, problems of implementation were not considered in detail. The approaches which received the greatest attention include: thermal radiation by injected particles and inserted intensifiers, acoustic energy, penetration of thermal wave by back flow of combustion gases into either perforated propellants or embedded porous elements, injection of burning rate catalysts, rammed propellant surfaces, and resistive heating. Other methods which were surveyed include: partial quenching, heating through vibration, induced unstable burning, dielectric heating, resistive wire networks, electrical and electromagnetic effects on flames and ingredient decomposition, acceleration forces, and utilization of photochemical processes. The thermal radiation methods should produce 10-50% increases in pressure level, but a practical radiation source is not apparent. The penetration of thermal waves into perforated propellants offers a wide range of control (> 10:1), but feasibility of controlled burning is not established. The embedded porous element approach should produce >8:1 control in high performance systems with reasonable developmental risks. Injection of catalysts is dependent on finding a method of delivering micron size particles to the propellant reaction zones. Two propellants of dissimilar composition, when rammed together, may produce a very wide range of control. Radiation and electrical methods which accelerate the decomposition of some propellant ingredients are largely untried and offer potential. The results emphasize that the merit and practicality of each method is largely dependent on the application.

Based on work performed under Contract F04611-69-C-0067 and was monitored by the Air Force Rocket Propulsion Laboratory (AFRPL), Edwards, Calif.

Accession No. AD873576L - Available from DDC.

"COMMAND CONTROL OF SOLID PROPELLANT BURNING RATE"

Leonard H. Caveny, Martin Summerfield

Proceedings of 7th JANNAF Combustion Meeting, Vol. 1, CPIA Publication 204, Feb. 1970, pp 35-59.

Analytical studies and surveys of command control of burning rate methods were performed. Approaches studied include: thermal radiation by injected particles and inserted intensifiers, acoustic energy, injection of burning rate catalysts, rammed propellant surfaces, and resistive heating. Other methods briefly commented on include: induced unstable burning, dielectric heating, and utilization of photochemical processes.

Based on work performed under contract F04611-69-C-0067 issued by the Air Force Rocket Propulsion Laboratory, Air Force Systems Command, Edwards, California

Accession No. for entire volume - AD882104L - Distribution Controlled - Not Available from DDC - Available only from CPIA.

I. C.
Steady State Burning
- General

"REVIEW OF WORKSHOP ON TEMPERATURE SENSITIVITY OF SOLID PROPELLANT BURNING RATE"

Leonard H. Caveny

Proceedings of the 9th JANNAF Combustion Meeting, Vol. II, CPIA Publication 231, Dec. 1972, pp. 197-215.

This review summarizes the results and conclusions of the one-day workshop sponsored by the Workshop Committee of the JANNAF Working Group on Combustion and was held on 17 September 1971 at Monterey, California in conjunction with the 8th JANNAF Solid Propellant Combustion Meeting. Following the precedent established for such workshops, the recommendations and conclusions in this paper represent the consensus of the investigators who participated in workshop. In several cases individual exceptions to the consensus are noted. However, it is emphasized that no attempt was made to arrive at a consensus with respect to physical arguments such as the validity of particular physical models and sites of catalyst action.

The effort associated with preparing this review was supported by contract N00014-67-A-0151-0023 issued by the Power Branch of the Office of Naval Research.

Accession No. for entire volume - AD906895L - Distribution Controlled - Not Available from DDC - Available only from CPIA.

"ACOUSTIC EMISSIONS FROM BURNING PROPELLANT STRANDS."

A. J. Saber, M. D. Johnston, L. H. Caveny, M. Summerfield and J. L. Koury

Proceedings of 11th JANNAF Combustion Conference, 1974, CPIA Publication No. 261, Vol. I, pp. 409-427.

Burning solid propellants produce ultra-high frequency acoustic emissions (UHFAE) which can be detected by a piezoelectric microphone mounted on the outside wall of a strand burner. Previous investigations of solid propellant UHFAE examined the gross aspects of the emissions, i.e., stop/start of the emissions for timing burning intervals and relative RMS signal levels; the objectives of this study include: (1) developing techniques to establish the spectral distribution (i.e., an acoustic emission spectrometer), (2) relating the spectra to particulars of the combustion process, (3) determining whether specific propellants are identifiable from their acoustic signatures, and (4) establishing a basis for recognizing spurious behavior from UHFAE signatures. Most of the effort is directed at the frequencies between 100,000 and 300,000 Hz generated during the combustion of aluminized (20%) and non-aluminized ammonium perchlorate composite propellants (granulation from 0.5 to 400μ) burned under water at constant pressure (30 to 140 atm). Experimental parameters include burning medium, reproducibility, test interval, pressure, strand size, oxidizer size and particle distribution. Systematic tests produced consistent trends of acoustic power versus frequency; although the spectra obtained do not permit specific combustion characteristics to be isolated. Exploration of the spectral structure is continuing.

Based on work performed under Grant AF-74-2602 sponsored by the Directorate of Aerospace Sciences, Air Force Office of Scientific Research and Army Contract DAAA21-72-C-0332 sponsored by the U.S. Army Product Assurance Laboratory of Picatinny Arsenal.

"INFLUENCE OF THERMAL RADIATION ON SOLID PROPELLANT BURNING RATE."

L. H. Caveny, T. J. Ohlemiller and M. Summerfield

AIAA Journal, Vol. 13, No. 2, February 1975, pp. 202-205.

Radiation assisted burning rate data $[r(q_{rad})]$ and temperature sensitivity of burning rate data $[r(p,T)$ and $\sigma_p = \partial r/\partial T_0)_p]$ were obtained for a well characterized double base propellant (nitrocellulose and metriol trinitrate). For example, at 14.6 atm, 70 cal/sec-cm^2 of xenon arc radiation increased the burning from 0.2 to 0.6 cm/sec. Analysis of the heat feedback from the flame revealed that once $r(T_0)$ data are available, $r(q_{rad})$ data does not permit additional properties of the combustion zone to be deduced. However, a simple analytical relationship between $r(q_{rad})$ and σ_p was developed that approximates the measured results. Propellant burning rate responsiveness to external thermal radiation increases with higher σ_p and lower burning rate.

Based on work performed under Grant AF74-2602 sponsored by the Energetics Division, Air Force Office of Scientific Research.

"COMBUSTION OF HIGHLY CATALYZED PROPELLANTS UNDER CONDITIONS OF RAPID PRESSURIZATION"

L. H. Caveny, M. Summerfield and B. B. Stokes

Proceedings of 12th JANNAF Combustion Meeting, Vol. II, CPIA Publication 273, Chemical Propulsion Information Agency, Laurel, MD, August 1975, pp. 403-424.

Migration of burning rate catalyst from high burning rate propellants has been associated with rocket motor failures and anomalous burning. At the onset of this experimental study, it was hypothesized that micropores formed by catalyst migration provided pathways for penetrative burning which was the precursor to propellant break-up. An experiment was developed which subjected propellant-bond-to-steel specimens to high pressurization rates (typically 20.7 GP_a/sec) (3 x 10^6 psi/sec) at 20.7 MPa (3000 psi). Examination of the pressure-versus-time records and extinguished specimens lead to the identification of four modes of failure associated with rapid pressure and ignition: (1) penetrative burning localized along a plane within the propellant (flat worm holing), (2) accelerated burning at the propellant liner interface, (3) propellant liner pull-away (debond), and (4) propellant break-up (catastrophic penetrative burning). Storage conditions and propellant-to-case bonds which minimize the loss of catalyst from the propellant resulted in test specimens which burned in a well-behaved manner.

Based on work performed under sponsorship by the Army Missile Command under contract No. DAAH01-74-C-0458.

Accession No. for entire Volume - AD-B009 580 - Distribution Controlled. Not available from DDC. Available only from CPIA.

"PROPELLANT BURNING RATE AND COMBUSTION UNIFORMITY IDENTIFIED BY ULTRASONIC ACOUSTIC EMISSIONS"

L. H. Caveny, A. J. Saber, and M. Summerfield

AMS Report No. 1302, Princeton University, Princeton, N.J., January 1976.

A new method of measuring the burning rate of as-manufactured grains of nitrocellulose-based propellants was developed. Chamber pressurization to 50,000 psi (3400 atm) was achieved using a hydraulic pump, rather than a nitrogen intensifier system; the burning interval was monitored by recording the acoustic emission from the burning propellant. Burning rate variations of nitrocellulose-based propellants (M1 and M26), burning at pressures between 10,000 and 40,000 psi, were recognized by examining the level of the combustion-generated acoustic emissions. Multi-perforated propellant grains were burned lengthwise (1 to 1.5 cm) and the RMS level of ultra-high frequency acoustic emissions were recorded. The burning rate variations of single-base propellants are attributed to incomplete dispersion of fibrous nitrocellulose. The double-base propellants produced neither irregularities in their acoustic emissions nor unusual variations in burning rate. These uniformities are attributed to the nitroglycerin which acts to disperse the nitrocellulose and to enhance burning rate.

Based on work performed under sponsorship of the U.S. Army under Contract DAAA21-74-C-0332.

Accession number AD . Available from NTIS.

"PROPELLANT COMBUSTION AND BURNING RATE UNIFORMITY IDENTIFIED BY ULTRASONIC ACOUSTIC EMISSIONS"

L. H. Caveny, A. J. Saber and M. Summerfield

AIAA Paper No. 76-696, July 1976, New York: American Institute of Aeronautics and Astronautics.

Burning rate variations of nitrocellulose-based propellants (M1 and M26), burning at pressures between 10,000 and 40,000 psi, are recognized by examining the level of the combustion-generated acoustic emissions. Multiperforated propellant grains are burned lengthwise (1 to 1.5 cm) and the RMS level of ultra high frequency acoustic emissions are recorded. The burning rate variations of single-base propellants are attributed to incomplete dispersion of fibrous nitrocellulose. The double-base propellants produced neither irregularities in their acoustic emissions nor unusual variations in burning rate. These uniformities are attributed to the nitroglycerin which acts to disperse the nitrocellulose and to enhance burning rate.

Based on work performed under sponsorship of the U.S. Army under Contract DAAA21-74-C-0332.

"FLAME ZONE AND SUB-SURFACE REACTION MODEL FOR DEFLAGRATING RDX"

M. BenReuven, L. H. Caveny, R. J. Vichnevetsky and M. Summerfield

To appear in Proceedings of 16th International Symposium on Combustion, August 1976.

A study of 1,3,5 Trinitro Hexahydro 1,3,5 Triazine, RDX, burning as a monopropellant was undertaken to obtain a better understanding of the important chemical steps that control heat feedback to the condensed phase, to determine the contributions of the liquid layer, and to provide a means of evaluating theories for modifying the burning rate of nitramines. The following chemical mechanism is proposed: first, partial decomposition of the RDX molecule in the liquid phase; second, following vaporization, gas phase decomposition of RDX; third, oxidation of formaldehyde by NO_2. The flame structure and liquid layer reactions of deflagrating RDX were expressed in terms of the energy, continuity, and species equations corresponding to RDX decomposing in liquid and gaseous phases and the NO_2/CH_2O reactions adjacent to the surface. In addition to the temperature profile and burning rate, the numerical solution provides the details of the interactions at the liquid/gas interface and the concentration profiles for the nine most prominent species. Using published kinetic data, the calculated results reveal that even though the liquid layer becomes thinner with increasing pressure, the increase in surface temperature causes its heat feedback contribution to increase. The pressure sensitivity of burning rate between 0.7 and 0.8 is interpreted in terms of the relative contributions of gas phase and liquid layer RDX decomposition and the oxidation of CH_2O. In particular, as pressure increases, the contribution from liquid layer reactions and the second order, NO_2/CH_2O reaction become more prominent.

Based on work performed under Contract N00014-75-C-0705 sponsored by the Power Branch of the Office of Naval Research.

Available through your local library system.

II UNSTEADY BURNING, COMBUSTION INSTABILITY AND EXTINGUISHMENT

II. Unsteady Burning, Combustion Instability and Extinguishment.

II UNSTEADY BURNING, COMBUSTION INSTABILITY AND EXTINGUISHMENT

"NONSTEADY BURNING PHENOMENA OF SOLID PROPELLANTS: THEORY AND EXPERIMENTS"

H. Krier, J. S. T'ien, W. A. Sirignano and M. Summerfield

AIAA Journal, Vol. 6, No. 2, Feb. 1968, pp. 278-285.

Nonsteady burning of solid propellants is being investigated both theoretically and experimentally, with attention to combustion instability, transient burning during motor ignition, and extinction by depressurization. The theory is based on a one-dimensional model of the combustion zone consisting of a thin gaseous flame and a solid heat-up zone. The nonsteady gaseous flame behavior is deduced from experimental steady-burning characteristics; the response of the solid phase is described by the time-dependent Fourier equation. Solutions were obtained for dynamic burning rate, flame temperature, and burnt gas entropy under different pressure variations; two methods were employed. First, the equations were linearized and solved by standard techniques. Then, to observe nonlinear effects, solutions were obtained by digital computer for prescribed pressure variations. One significant result is that a propellant with a large heat evolution at the surface is intrinsically unstable under dynamic conditions even though a steady-state solution exists. Another interesting result is that the gas entropy amplitude and phase depend critically on the frequency of pressure oscillation and that either near-isentropic or near-isothermal oscillations may be observable. Experiments with an oscillating combustion chamber and with a special combustor equipped for sudden pressurization tend to support the latter conclusion.

Based on work performed under Contract AF49(638) 1405 issued by the Propulsion Division, Air Force Office of Scientific Research. This is the latest version of AMS Report 793 (AFOSR Technical Report 67-1535) AD-658049.

Accession No. A68-16711# - Available from AIAA.

"ERRORS IN NONSTEADY COMBUSTION THEORY IN THE PAST DECADE (A REVIEW)"

Martin Summerfield and Herman Krier

AIAA Paper No. 69-178, Jan. 1969. New York: American Institute of Aeronautics and Astronautics.

All nonsteady combustion theories are based on nonsteady gasdynamics coupled to some particular nonsteady burning process. In past work, the gasdynamic aspect has usually been formulated quite well, although solutions have sometimes been difficult to extract. Amazingly, however, the burning process has almost always been badly modeled physically or badly represented mathematically. Serious errors of this kind exist in many published theories of nonsteady gaseous combustion, nonsteady liquid fuel combustion, and nonsteady solid propellant combustion. Three classes of error are prominent: (1) Incorrect (even heedless!) mathematical representation of physical flame structures; (2) Incorrect interface conditions in the case of heterogeneous flames; (3) Incorrect application of quasi-steady approximations to complex nonsteady flames. Illustrations are drawn from 30-odd prominent papers of the last decade. Many theories of combustion instability, explosions through sprays, extinction of burning solid propellants, etc., are suspect; the predictions may be grossly wrong.

Based on work performed under Contract AF49(638)-1405 issued by the Air Force Office of Scientific Research and Contract DAAD05-68-C-0450 issued by the U.S. Army.

Accession No. A69-18100# - Available from AIAA.

"ROLE OF ALUMINUM IN SUPPRESSING INSTABILITY IN SOLID PROPELLANT ROCKET MOTORS"

Martin Summerfield and Herman Krier

Sixtieth Anniversary Volume in Honor of L. I. Sedov; April 1969, Society of Ind. and Appl. Math., Philadelphia, Pa., pp. 703-717.

Combustion instability in large high-performance solid propellant rocket motors was a major difficulty standing in the way of practical development in the United States, until the discovery in 1956, after much testing, that powdered aluminum added to the propellant suppresses instability. This discovery made it possible for the national solid rocket program to move forward rapidly. The exact mechanism of the action of aluminum has long been a mystery. Aluminum is almost unique in its effectiveness; magnesium is the only other additive known to be equally effective. A theory is advanced in this paper, based on the previously published KTSS theory of nonsteady propellant burning, to the effect that it is the melting of the aluminum on the burning propellant surface, not its particular burning characteristics, that reduces the amplitude of the propellant burning rate fluctuations. The melting leads to the formation of a thin layer of molten aluminum that, through its thermal inertia, reduces the temperature response of the surface and therefor the burning rate response. The stabilizing mechanism is powerful: a very thin layer with only partial coverage of the surface produces a very large reduction in the acoustic admittance. Unfortunately, aluminum is objectionable (magnesium, too) because it produces smoke, flash, and ions in the exhaust jet. The paper concludes with an assessment, on the basis of the KTSS theory, of the possibility of ever finding an equally effective substitute and with some directions for investigation.

Based on work performed under contract AF49(638)-1405, issued by the Air Force Office of Scientific Research. Most recent version of report by same authors which was AFOSR Technical Report 69-2558 (AD 694-969).

Accession No. AD694969 - Available from NTIS.

"ENTROPY WAVES PRODUCED IN OSCILLATORY COMBUSTION OF SOLID PROPELLANTS"

H. Krier, M. Summerfield, H. B. Mathes and E. W. Price

AIAA Journal, Vol. 7, No. 11, Nov. 1969, pp. 2079-2086.

The dynamic response of a flat solid-propellant flame to an oscillating pressure field was studied experimentally in a window burner fitted to a T-tube rocket motor that served as a pressure oscillator. The burned gas temperature was measured as a function of time (or phase) during a pressure oscillation, and also as a function of distance from the surface. Such instantaneous measurements of gas temperature, when coordinated with simultaneous measurements of pressure, provide a measure of the entropy content of each element of gas as it flows away from the flame. Since the entropy content of each element of gas is nearly conserved as it flows along, an entropy wave train is formed. It is possible to make deductions regarding the physics of the dynamic burning process by comparing the magnitude and phase of the observed entropy waves with the theoretical values predicted on the basis of a particular flame model. In general, the results show that the temperature of the gas flowing from the combustion zone responds neither isentropically nor isothermally to the pressure. Such responses were assumed in previous publications on the subject. However, on the basis of the KTSS model published recently, the magnitude and phase of the entropy wave are expected to vary in a more complicated form with the imposed frequency and the propellant properties. The observed waves reported in this paper tend to support these KTSS theoretical expectations.

Based on work performed under Contract AF 49 (638)-1405 issued by the Propulsion Division, Air Force Office of Scientific Research, and parallel research at the Naval Weapons Center.

Accession No. A70-15580# - Available from AIAA. Accession No. identifies AIAA Paper 68-499 which is superseded by above Journal.

"THEORY OF L-STAR COMBUSTION INSTABILITY WITH TEMPERATURE OSCILLATIONS"

J. S. T'ien, W. A. Sirignano and M. Summerfield

AIAA Journal, Vol. 8, No. 1, Jan. 1970, pp. 120-126.

Low-frequency nonacoustic instability of solid-propellant rocket motors is being investigated by adopting a combustion model which allows the flame temperature to oscillate with the chamber pressure. Two different chamber gasdynamic situations are analyzed; in one the chamber gases are without dissipation and mixing and in the other they are well-stirred which eliminates entropy waves. The neutral stability lines are found to depend on the propellant and steady-state parameters and the nondimensional gas residence time in the chamber. Comparison with the results under isothermal conditions shows that the temperature oscillations have a destabilizing effect, especially when the nondimensional gas residence time is small. When the nondimensional gas residence time is large, the stability boundaries approach the boundary of intrinsic instability of the burning rate. Comparison of experimental data with theoretical predictions has been made. Its results indicate that the qualitative aspects of the model are correct, the quantitative predictions are sufficiently close that a more critical comparison is needed. And this, in turn, requires more precise measured data of the propellant surface temperature and the surface activation energy.

Based on work performed under Contract AF49(638) 1405 issued by the Propulsion Division, Air Force Office of Scientific Research.

Accession No. A70-19319# - Available from AIAA.
Supersedes AIAA Paper #68-179.

"NON-STEADY COMBUSTION OF SOLID PROPELLANTS"

R. A. Battista, L. H. Caveny and M. Summerfield

Aerospace and Mechanical Sciences Report No. 1049, Oct. 1972
Princeton University, Princeton, N.J.

Solid rocket performance during rapid pressure excursions differs greatly from predictions based on steady-state burning rate data. Rapid pressurization (150 to 250 kpsi/sec) following a sudden throat area decrease in a low L* combustor produces pressure overshoots of 10% and indicated burning rate overshoots in excess of 50%. A transient internal ballistics model was developed incorporating nonsteady continuity and energy equations for the chamber, nonsteady energy equation for the propellant condensed phase, and a modified Zeldovich heat feedback function for the propellant (which for the conditions considered is known to burn a thin quasi-steady reaction zone). Sensitivity analyses using the model indicate that accurate surface temperature and temperature sensitivity data are needed. With reasonable estimates of surface reaction zone temperature and measurements of temperature sensitivity of burning rate, good agreement between the measured and the calculated p vs t was found for a non-metallized composite propellant in a low L* combustor. High pressure exponent, high temperature sensitivity of burning rate, high dA_t/dt, low burning rate, and low L* prominently increase the dynamic effects.

Based on work performed under contract N00014-67-A-0151-0023 sponsored by the Power Branch, Office of Naval Research.

Accession No. AD753835 - Available from NTIS.

"DYNAMIC RESPONSES OF SOLID ROCKETS DURING RAPID PRESSURE CHANGE"

S. L. Turk, R. A. Battista, K. K. Kuo, L. H. Caveny and M. Summerfield

Journal of Spacecraft and Rockets, Vol. 10, No. 2, Feb. 1973, pp 137-142.

Solid rocket performance during rapid pressure excursions differs greatly from predictions based on steady-state burning rate data. Rapid pressurization (150-250 kpsi/sec) following a sudden throat area decrease in a low L* combustor produces pressure overshoots of 10% and indicated burning rate overshoots in excess of 50%. A transient internal ballistics model was developed incorporating nonsteady continuity and energy equations for the chamber, nonsteady energy equation for the propellant condensed phase, and a modified Zeldovich heat feedback function for the propellant (which for the conditions considered is known to burn with a thin quasi-steady reaction zone). Sensitivity analyses using the model indicate that accurate surface temperature and temperature sensitivity data are needed. With reasonable estimates of surface reaction zone temperature and measurements of temperature sensitivity of burning rate, good agreement between the measured and the calculated p vs t was found for a non-metallized composite propellant in a low L* combustor. High pressure exponent, high temperature sensitivity of burning rate, high dA_t/dt, low burning rate, and low L* prominently increase the dynamic effects.

Based on work performed under contract N00014-67-A-0151-0023 issued by the Power Branch of the Office of Naval Research.

Available through your local library system and/or from the Engineering Societies Library, New York, N.Y. Abstract 045 584, Engineering Index 1973.

"IGNITION TRANSIENTS AND PRESSURIZATION IN CLOSED CHAMBERS."

L. H. Caveny, M. Summerfield and C. W. Nelson

Proceedings of the 11th JANNAF Combustion Conference, 1974, CPIA Publication No. 261, Vol. 1, pp. 433-457.

Pressure versus time data obtained from igniting and burning propellants in highly loaded closed chambers (loading densities between 0.1 and 0.4 g/cm^3) are being used to evaluate propellants in empirical quality and production control procedures. Interpretations obtained from such production control devices are hampered by uncertainties concerning ignition delays, dynamic burning, heat loss, propellant surface area versus distance burned, and real gas effects. In this study, attention is focused on devising a closed chamber experiment for measuring dynamic burning rates and on developing a comprehensive analytical model of the experiment. Features of the model include the energy equation, heat up to ignition, generalized real gas effects, and dynamic burning. Calculated results lead to improved methods for analyzing and reporting closed chamber results so as to include information on the dynamic processes that dominate ignition and the early stages of pressurization.

Based on work performed under Contract DAAD05-72-C-0135 sponsored by the U. S. Army.

Accession No. AD-A017 747. Available from NTIS. An expanded version was published as BRL Memorandum Report No. 2558, Ballistic Research Laboratories, Aberdeen Proving Ground, MD, Nov. 1975.

"PROPELLANT COMBUSTION DYNAMICS IN CLOSED CHAMBERS."

L. H. Caveny, M. Summerfield and C. W. Nelson

Proceedings of ADPA First International Symposium on Ballistics, Orlando, Fla., 13-15 November 1974.

Advances in closed chamber technology are described and analyzed within the context of their applications in predicting and understanding gun performance: (1) a mathematical model of the ignition, energy transfer, and pressurization sequences in closed chambers, and (2) a proposed closed chamber specifically designed to determine ignition and dynamic burning responses. Attention is focused on the distinction between the production control requirements of establishing the charge weight for a gun with a well behaved ignition and pressurization sequence and the requirements for improved predictive techniques in the formative stages of development. The analytical model of closed chamber processes developed for this study considers heat-up-to-ignition followed by chamber pressurization, by accounting for the close coupling between the propellant thermal response and the transient pressure and temperature responses of the chamber gases. The features of the solution to the energy and continuity equations include a generalized equation of state, heat losses, contributions of the igniter charge, and dynamic responses of burning rate and flame temperature. Calculated results stress: (1) the importance of complete treatments of ignition and nonsteady burning in analyzing conditions that can lead to pressure oscillations, and (2) the importance of high precision burning rate data if internal ballistic codes are to be used to assess the effects of small propellant formulation and configuration variations.

Based on work performed under Contract DAAD05-72-C-0135 sponsored the U.S. Army Ballistic Research Laboratories.

"LONGITUDINAL MODE OSCILLATIONS IN AN END-BURNING SOLID ROCKET MOTOR."

J. S. T'ien and W. A. Sirignano

Proceedings of 6th ICRPG Combustion Conference, CPIA Publication No. 192, Vol. 1, December 1969, pp. 467-475.

This paper treats linear and nonlinear longitudinal mode oscillation in an end-burning solid rocket motor. The purpose is to determine the stability boundary, the amplitude of the finite wave oscillation, and the possibility of triggering. The amplification of the wave results from the combustion zone interaction and the damping results from the nozzle outflow. In this work, the KTSS combustion model has been assumed for the computations. Since the several existing unsteady combustion models of solid propellant have quite similar qualitative properties, many of the conclusions here apply in a more general way. Two kinds of nozzles have been employed; one is a very short nozzle, the other is a 30 degree linearly-tapered nozzle. The linear and nonlinear analyses are achieved by different mathematical procedures. In the linear case, the expansion parameter is the amplitude of the wave. In the nonlinear case, a double expansion is used, first an expansion in mean Mach number, and then an explansion in amplitude.

From the linear analysis it was shown that: (1) the neutral stability lines have loops appearing, but the real stability boundaries are those arcs without the loops, with the frequencies in each arc close to a classical acoustic mode, (2) a longer nozzle is much more stable than a shorter one, and (3) for intermediate values of the ratio of solid thermal time to chamber wave travel time, the end-burning solid rocket can be operated safely without either acoustic or nonacoustic instabilities. From the nonlinear analysis it was shown that the finite amplitude shock free oscillation can be found in the linear unstable domain near the linear boundary line, but triggering of shock wave using nonlinear impulse is not possible in an end-burning solid rocket motor.

Based on work performed under Contract AF49(638)1405 sponsored by the Propulsion Division, Air Force Office of Scientific Research.

Accession No. AD865675L. Available from DDC. Limited Distribution.

"EXTINGUISHMENT OF SOLID PROPELLANTS BY DEPRESSURIZATION: EFFECTS OF PROPELLANT PARAMETERS"

C. L. Merkle, S. L. Turk and Martin Summerfield

AIAA Paper No. 69-176, Jan. 1969. New York: American Institute of Aeronautics and Astronautics.

A new theory for extinction by depressurization of AP composite propellants is employed to predict the rate of pressure decrease required to achieve flame-out and to rationalize the effects of various composition parameters on the ease of extinguishment. Attention is given in this theory to the proper derivation of the nonsteady heat feedback from the gaseous flame zone to the burning surface. Included in the theory are the essential physical and chemical rate processes of the granular diffusion flame model, as deduced from steady-state burning characteristics. It is predicted theoretically that: (a) whether extinction occurs depends on the entire shape of the pressure transient, not just on the initial slope; (b) extinction depends on the pressure dependence of the steady state burning rate all the way down to the final pressure; (c) increasing the AP fraction, reducing the AP particle size, or adding fine aluminum powder makes a propellant more difficult to extinguish. These predictions are confirmed by experimental tests with AP composite propellants with PBAA, PB(CT), and PU binders.

Based on work performed under Contract Nonr 1858(32) sponsored by the Power Branch of the Office of Naval Research.

Accession No. A69-18102# - Available from AIAA.

"EXTINGUISHMENT OF SOLID PROPELLANTS BY RAPID DEPRESSURIZATION"

C. L. Merkle, S. L. Turk and M. Summerfield

Aerospace and Mechanical Sciences Report No. 880, July 1969, Princeton University, Princeton, N.J.

A new theory for extinction by depressurization of AP composite propellants is employed to predict the rate of pressure decrease required to achieve flame-out and to rationalize the effects of various composition parameters on the ease of extinguishment. The research is concentrated mainly on the "temporary" extinguishment behavior of solid propellants, but a re-ignition theory is also presented. Attention is given in this theory to the proper derivation of the non-steady heat feedback from the gaseous flame zone to the burning surface. Included in the model are the essential physical and chemical rate processes of the granular diffusion flame model, as deduced from the steady state burning characteristics. It is predicted theoretically that: (a) whether extinction occurs depends on the entire shape of the pressure transient, not just on the initial slope; (b) extinction depends upon the pressure dependence of the steady state burning rate all the way down to the final pressure; (c) increasing the AP fraction, reducing the AP particle size, or adding fine aluminum powder makes a propellant more difficult to extinguish. These predictions are confirmed by experimental tests with AP composite propellants with PBAA, PB(CT), and PU binders. A brief study of double-base propellants which indicates that they are considerably easier to extinguish than composite propellants concludes this report. A rough model for the burning of double-base propellants is presented which further indicates the importance of the flame structure in determining the extinguishment characteristics of solid propellants.

Supplement (AMS Report 880S) contains p vs t data and listings of computer programs.

Based on work performed under contract Nonr 1858(32) sponsored by the Power Branch, Office of Naval Research.

Accession No. AD697661 for AMS Report 880 and AD712116 for AMS Report 880S - Both available from NTIS.

"THEORY OF DYNAMIC EXTINGUISHMENT OF SOLID PROPELLANTS WITH SPECIAL REFERENCE TO NONSTEADY HEAT FEEDBACK LAW"

M. Summerfield, L. H. Caveny, R. A. Battista, N. Kubota, Yu. A. Gostintsev, and H. Isoda

Journal of Spacecraft and Rockets, March 1971, Vol. 8, No. 3, pp 251-258.

Two methods for predicting instantaneous burning rates are described and compared: (1) theories based on models of the flame and (2) the Zeldovich-Novozhilov method which uses the steady-state burning rate data as functions of pressure p and initial temperature T_0 to deduce the appropriate non-steady law for the heat feedback rate from the flame. The latter method offers the important advantage of not requiring detailed knowledge of the flame structure. Theoretical connections between the two methods are demonstrated. Burning rate data $r(p,T_0)$ were obtained for pressures from 1.3 to 40.0 atm and for initial temperatures from 130° to 350°K. The primary limitation encountered in the application of the Zeldovich-Novozhilov method is the inadequacy of techniques for obtaining $r(p,T_0)$ at ambient temperatures below 150°K. Calculated extinction boundaries agree with measured results for depressurization rates from 4,000 to 15,000 atm/sec and pressures from 20 to 60 atm. An interesting observation is that within a class of similar propellants, the propellant with a high temperature sensitivity of burning rate tends to extinguish more readily, ignite with greater difficulty, and be more prone to instability.

Based on work performed under contract N00014-67-A-0151-0023 issued by the Power Branch of the Office of Naval Research.

Accession No. A70-33949# - Available from AIAA. Above cited article supersedes AIAA Paper 70-667 (Accession No. A71-22905#).

III IGNITION OF PROPELLANTS AND FUELS

III Ignition of Propellants and Fuels

A. Radiative

B. Convective and Conductive

C. Liquids (including flame spreading).

D. General

III IGNITION OF PROPELLANTS AND FUELS

III IGNITION OF PROPELLANTS AND FUELS

III. A.
Ignition
- Radiative

"A CRITICAL ANALYSIS OF ARC IMAGE IGNITION OF SOLID PROPELLANTS"

T. J. Ohlemiller and M. Summerfield

AIAA Journal, Vol. 6, No. 5, May 1968, pp. 878-886.

The arc image furnace is used widely for evaluating solid-propellant ignition characteristics, but the applicability of such data to rocket motors is not well-established. In arc image testing, radiation replaces the normal conductive and convective heating modes that exist in rocket motor ignition; radiation interacts with the propellant in a basically different way. Thus, for example, because radiation is absorbed in depth, the ignition delay is sensitive to propellant opacity. In addition, radiation can cause subsurface disruption of the propellant. A physical model is proposed in which incident radiation penetrates the propellant and is absorbed, causing thermal and photochemical decomposition and a temperature increase. Oxidative reactions start either in the gaseous boundary layer or on the surface and, by thermochemical action, lead to a flame. The system of differential equations for this complete model is complicated and has not been solved. However, an equivalent model of simpler character is solved, and an equation is produced for the ignition time delay as a function of radiation intensity, pressure, and physico-chemical properties. This equation can be used for correcting arc image data to equivalent convective ignition data. The qualitative behavior of experimental radiative ignition data reported by Beyer and Fishman and by Bastress can be rationalized with the aid of this theory.

Based on work performed under Contract AF 49(638) 1267 issued by the Propulsion Division, Air Force Office of Scientific Research.

Accession No. A68-27083# - Available from AIAA.

"RADIATIVE IGNITION OF POLYMERIC FUELS IN AN OXIDIZING GAS"

T. J. Ohlemiller and M. Summerfield

Aerospace and Mechanical Sciences Report No. 876, Aug. 1969, Princeton University, Princeton, N.J.

The widespread use of a radiative energy source to study solid propellant ignition characteristics has generated the need for a closer examination of the processes comprising ignition by radiation. The manner in which radiation interacts with a composite propellant and subsequently heats it is shown to pose an inherently three-dimensional scattering and heat conduction problem for most practical cases; the complexity of the problem precludes exact treatment. Radiative ignition of a pure fuel in an oxidizing gas is proposed as a useful simplified analog of propellant ignition. A simple approximate solution for the radiative ignition of a condensed material is derived by considering several asymptotic cases in which individual factors dominate the ignition delay. A radiative ignition apparatus employing a CO_2 laser has been used to study the effects of radiant flux, pressure, oxygen concentration, and absorptivity on the ignition delay of polystyrene and an epoxy polymer in oxygen/nitrogen mixtures. The results are shown to agree well with the approximate radiative ignition solution if an ignition temperature of approximately 600°C is accepted. This large value of ignition temperature is believed to be a consequence of both retarded fuel vaporization due to transient effects in the polymers and to the reaction suppressing character of the cold gas adjacent to the fuel surface.

Based on work performed under Contract AF-69-1651 sponsored by the Air Force Office of Scientific Research, Office of Aerospace Research, U.S. Air Force.

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"RADIATIVE IGNITION OF POLYMERIC MATERIALS IN OXYGEN/NITROGEN MIXTURES"

T. J. Ohlemiller and M. Summerfield

Thirteenth Symposium (International) on Combustion, The Combustion Institute, 1971, pp. 1087-1094.

The radiative ignition behavior of two polymeric fuels - polystyrene and an epoxy - in oxygen/nitrogen mixtures has been determined experimentally. A CO_2 laser was adapted for use as the radiation source to simplify interpretation of the results. Ignition delay (as determined by first light emission) was measured as a function of oxygen percentage, pressure, radiant flux, and fuel absorptivity. The observed ignition delays, and the variations with pressure, oxygen fraction, and radiation intensity, conform to the predictions of a theoretical model based on the need to heat the surface to a critical ignition temperature. The most important finding is that ignition of a solid fuel by radiation is much slower than ignition by an identical heat flux applied by a hot gas source. Two main reasons for the retardation can be deduced from the experimental results: (1) the radiative transparency of the fuel, even for seemingly opaque substances, results in slower surface heating, and (2) the cool gas environment in the usual radiation ignition test suppresses the incipient ignition.

Based on work performed under contract AF69-1651, issued by the Propulsion Division, Air Force Office of Scientific Research.

Accession No. A71-38125 - Available from AIAA.

"DYNAMIC EFFECTS ON IGNITABILITY LIMITS OF SOLID PROPELLANTS SUBJECTED TO RADIATIVE HEATING"

T. J. Ohlemiller, L. H. Caveny, L. DeLuca, and M. Summerfield

Fourteenth Symposium (International) on Combustion, pp 1297-1307, The Combustion Institute 1973.

The dynamic response of a solid propellant to a rapidly varying radiation flux comprises a problem representative of the general class of transient responses of heterogeneous flames to rapid disturbances. In the present study, the response of double-base propellants to roughly square-wave radiation pulses is examined. It is found that, when such pulses are used to ignite propellants, they may in some cases produce a flame which persists for whatever duration the pulse persists, but which extinguishes as soon as the pulse stops. This tendency to extinction upon deradiation is found to be lessened by increased pressure or increased time interval for reducing the flux to zero. This extinction response upon deradiation is not limited to the ignition situation; it is shown experimentally that a steadily burning propellant can be extinguished by a radiation pulse of appropriate magnitude, duration, and speed of cut-off. It is proposed that this dynamic extinction behavior results from an imbalance in the heat fluxes to and from the burning surface during deradiation. A mathematical model of this phenomenon, deriving from the nonsteady burning approach of Zeldovich, is solved and shown to predict quite well the same type of behavior as that found experimentally.

Based on work performed under contract AF69-1651 issued by Propulsion Division, Air Force Office of Scientific Research, and under grant DA-ARO-D-31-124-71-G184 issued by the U.S. Army Research Office and monitored by the Ballistic Research Laboratories.

Available in book form from The Combustion Institute, Union Trust Building, Pittsburgh, Pa. 15219. Individual article available from AIAA as Accession No. A73-42813.

III A
Ignition
- Radiative

"IGNITION DYNAMICS OF DOUBLE BASE PROPELLANTS."

M. Summerfield, L. H. Caveny, T. J. Ohlemiller and L. DeLuca

Aerospace and Mechanical Sciences Report No. 1150, January 1974, Princeton University, Princeton, N.J.

Ignition and transient combustion characteristics of composite propellants (AP or HMX types) and double base propellants (NC/NG and NC/MTN types) were classified by their responses to strong radiant heating (5 to 100 cal/cm^2-sec) from laser and arc sources. Ignition times (go/no-go measurements) are significantly different for the two classes of propellant and are affected greatly by addition of carbon powder and/or combustion catalysts. The results reveal several important generalizations. With the arc furnace the opacifiers in the condensed phase can lower the ignition times as much as tenfold. For double base propellants, the time to the IR emission level corresponding to the onset of surface decomposition is independent of pressure and O_2 concentration, whereas the time to sustained flame (go/no-go test) depends on both. A mathematical model for ignition and the nonsteady burning following ignition, employing the non-steady heat feedback function of Zeldovich, was solved and shown to predict quite well the same type of behavior as that found experimentally. The problem of relating convective ignition response (needed for rocket and other applications) to radiative ignition test results was shown to be complicated by the inherent characteristics of radiation experiments, i.e., propellant reflectivity and transparency, slow kinetics in the cool gas phase, dynamic extinction during deradiation, and spatial variation of radiation flux on the target surface.

Based on work performed under Grant DA-ARO-D-31-124-72-G119 sponsored by the U.S. Army Research Office in Durham and monitored by the Ballistic Research Laboratories, Aberdeen Proving Ground, Md.

Not cataloged by DDC. Available from Interlibrary Loans, Princeton University Library, Princeton, N.J. 08540

"RADIATIVE IGNITION OF DOUBLE-BASE PROPELLANTS: I. SOME FORMULATION EFFECTS"

L. DeLuca, L. H. Caveny, T. J. Ohlemiller and M. Summerfield

AIAA Journal, Vol. 14, No. 7, July 1976, pp. 940-946.

In this first paper of a two part study, the ignition response to arc image radiative heating (5 to 100 cal/cm^{2}sec) of several double-base propellants is examined; comparisons with certain AP and HMX propellants are made also. Ignition delay is affected by chemical factors in propellant formulation (stability of the condensed phase, reaction rate in the gas phase) and by optical factors in propellant formulation (opacifiers affecting reflectivity and in-depth absorption). The results show that comparisons of the chemical factors in the formulation can only be made properly when the optical factors are minimized (as by carbon addition). When optical factors are minimized by opacifying the propellant, one finds, in order of increasing ease of ignitability, the formulations tested fall as follows: HMX composite, AP composite, double base (noncatalyzed), double base (catalyzed).

Based on work performed under sponsorship of U.S. Army Research Office under Grant DA-ARO-D-31-124-72-G119.

Accession No. A76-39436. Available from AIAA.

III. A.
Ignition
- Radiative

"RADIATIVE IGNITION OF DOUBLE BASE PROPELLANTS: II. PRE-IGNITION EVENTS AND SOURCE EFFECTS

L. DeLuca, T. J. Ohlemiller, L. H. Caveny and M. Summerfield

AIAA Journal, Vol. 14, No. 8, August 1976, pp. 1111-1117.

In this second paper of a two-part study, emphasis is on the pressure dependent pre-ignition events in double base propellants and the influence of radiation source (arc image vs laser) on observed ignition behavior. The pressure-dependent (< 21 atm) ignition domain of a PNC/MTN double base propellant is examined using controlled exposure lengths together with high speed movies and an infrared detector to monitor flame development after gasification begins; this is followed by a relatively long, flux-dependent period of steady-state, radiation assisted burning before a self-sustaining condition is reached. The nature of this condition for self-sustainment is not yet well-defined. The ignition behavior seen with an arc furnace or a laser is generally quite close for both double base and composite propellants, if optical effects (reflection, penetration) are factored out. An exception is fast deradiation extinction, seen only with the laser; greater radiation penetration in the arc image wavelength region precludes this phenomenon.

Based on work performed under sponsorship of U.S. Army Research Office under Grant DA-ARO-D-31-124-72-G119.

Accession No. A76-41703 (Also AIAA Paper 73-176). Available from AIAA.

"IGNITION OF A SOLID POLYMERIC FUEL IN A HOT OXIDIZING GAS STREAM"

T. Kashiwagi, B. W. MacDonald, H. Isoda and M. Summerfield

Proceedings of Thirteenth (International) Symposium on Combustion, Aug. 1970, pp. 1073-1086.

The ignitability of a solid fuel by a hot oxidizing gas stream was studied experimentally in a hot-gas wind tunnel of the shock-tube type, with a flat-plate fuel specimen placed parallel to the flow. The problem was analyzed theoretically as a boundary-layer flow field adjacent to the fuel surface, in which the thin reaction zone grows more intense with time. Two alternative mechanisms were postulated as responsible for the development of ignition, one an exothermic gas-phase reaction in the boundary layer, and the other a heterogeneous reaction at the solid surface. Each of the two theories takes into account the changing profiles within the boundary layer during the induction period prior to ignition, the simultaneously changing thermal profile below the surface of the fuel due to convective heating, and the gradually rising rate of reaction. Ignition is said to occur at that time and at that location at which the reaction rate reaches a suitably defined runaway condition. The surface-reaction model predicts that ignition will always occur near the leading edge of the plate of fuel; although the ignition time is sensitive to the oxygen concentration, gas temperature, and other physical parameters, the location of ignition is not. The gas-phase model, however, predicts that ignition will occur at some downstream position, the distance increasing with increasing flow velocity and with decreasing oxygen concentration. Observations of the onset of ignition and of boundary-layer events during the induction period were made with submillisecond resolution times with high-speed cine-shadowphotography and with UV-filtered photocells focused on the fuel plate. The photographs depict the development of the ignition reaction with exceptional clarity. The findings as to location of ignition conform to the predictions of the gas-phase reaction theory and not the surface reaction theory. It is concluded that ignition of a solid polymeric hydrocarbon fuel (PBAA) in hot oxygen/nitrogen mixtures occurs mainly by means of a gas-phase reaction in the boundary layer, the reactants being the oxygen of the hot-gas stream and the fuel-like gases evolved from the pyrolytic heating of the solid fuel.

Based on work performed under contract AF69-1651 issued by the Propulsion Division, Air Force Office of Scientific Research.

Accession No. A71-38124 - Available from AIAA.

"IGNITION OF SOLID POLYMERIC FUELS BY HOT OXIDIZING GASES"

T. Kashiwagi, B. W. MacDonald, H. Isoda and M. Summerfield

Aerospace and Mechanical Sciences Report No. 947, Oct. 1970, Princeton University, Princeton, N.J.

The highly complex nature of composite propellants has led to several postulates as to the controlling element of their ignition mechanism; exothermic chemical reactions in the condensed phase, on the surface, and in the gas phase, have been proposed. In an attempt to identify the rate-controlling exothermic reaction, one-dimensional conduction mode experiments with a shock tube and two-dimensional convective mode experiments with a shock tunnel were performed with pure polymer and propellant specimens. The one-dimensional experimental results could be matched with previously published predictions based on any model by choosing suitable values of physical and chemical parameters. Also, the experimental data indicated the inadequacy of a model which assumes a homogeneous propellant with a single pyrolysis law at the surface.

Two-dimensional mathematical models describing both gas phase and surface reaction controlled ignition of a pure fuel in an oxidizing boundary layer were developed and solved numerically. The difference is predicted behavior of the first ignition position became the basis for a two-dimensional experimental effort to find out which model conforms to the real situation. The experimental data agreed with the predicted phenomenological trends based on a gas phase reaction and did not agree with the surface reaction prediction.

Based on work performed under Contract AF-69-1651 sponsored by the Air Force Office of Scientific Research, Office of Aerospace Research.

Accession No. AD746042 - Available from NTIS.

"IGNITION AND FLAME SPREADING OVER A SOLID FUEL: NON-SIMILAR THEORY FOR A HOT OXIDIZING BOUNDARY LAYER"

T. Kashiwagi and M. Summerfield

Proceedings of Fourteenth Symposium (International) on Combustion, 1973, The Combustion Institute, pp. 1235-1247.

A more accurate theoretical study of ignition of a solid polymeric fuel in a hot oxidizing flow field is carried out as an extension of the previous work reported in the Thirteenth Combustion Symposium. In the present work, the complete non-similar calculation is carried out, eliminating the previously used local similarity approximation and the integral approximation to solve the condensed-phase energy equation. Comparison of the predictions based on the non-similar calculations indicates that both results predict similar trends of ignition behavior. However, the ignition delay time and the amount of downstream shift in the previous local similarity calculation differ significantly from those in the present non-similar calculation. This comparison has implications for other theories of boundary layer combustion in the literature that utilize the self-similarity approximation. The flame-spreading behavior is also predicted as an extension of the ignition process. In agreement with the experimental observations reported in the previous works, results of the non-similar calculation predict that, in the case of high freestream oxygen concentration, the flame spreading downstream from the point of first ignition is slow. Reducing the oxygen concentration increases the flame-spreading speed in both directions (upstream and downstream). This agreement between experiment and theory indicates that, when the flame spreads downstream, convective heat transfer is the dominant process in bringing the local surface element to vigorous pyrolysis, rather than conduction, and when the flame spreads upstream in the low freestream oxygen level case, the surface temperature ahead of the flame front is already high enough to cause spontaneous ignition, and the appearance of flame awaits the evolution of an abundant supply of fuel. Ignition and flame spreading are shown theoretically to depend sensitively on the thermal and transient properties of the diluent gas (e.g., helium, argon, nitrogen).

Based on work performed under Contract AF 69-1651 issued by the Propulsion Division, Air Force Office of Scientific Research.

Available in book form from The Combustion Institute, Union Trust Building, Pittsburgh, Pa. 15219. Individual article available from AIAA as Accession No. A73-42809.

"IGNITION OF POLYMERS IN A HOT OXIDIZING GAS"

T. Kashiwagi, C. H. Waldman, R. B. Rothman and M. Summerfield

Combustion Science and Technology, Vol. 8, No. 3, 1973.

Experiments were performed using a shock tube in which both pure polymer and propellant specimens, mounted on the end wall, are suddenly exposed to a hot stagnant gas at about 1800 °K and 47 atm. The test gas consists of oxygen/nitrogen mixtures in which the oxygen mole fraction is varied from 0.18 to 1.00. The resultant ignition delay is observed to increase sharply as the mole fraction of oxygen is reduced and typical ignitability limits are 0.2 ∿ 0.3 mole fraction or 10 ∿ 15 atm oxygen partial pressure. Ignition delay time is found to be sensitive to total pressure as well as partial pressure. The effect of imbedded oxidizer is found to be significant when the ambient oxygen mole fraction is below 0.5 mole fraction. The theoretical ignition delay predictions of the gas phase and heterogeneous theories are shown to be too close for the experimental data to distinguish between them. A simple flat-surface stagnant exposure (a one-dimensional model) is found to be inadequate to resolve the question as to the dominant reaction in the ignition mechanism.

Based on work performed under Contract AF69-1651 sponsored by the Energetics Division of the Air Force Office of Scientific Research.

Not yet cataloged - available through your local library system.

"EXPERIMENTAL STUDY OF IGNITION AND SUBSEQUENT FLAME SPREAD OF A SOLID FUEL IN A HOT OXIDIZING GAS STREAM."

T. Kashiwagi, G. G. Kotia and M. Summerfield

Combustion and Flame, Vol. 24, 1975, pp. 357-364.

Characteristics of ignition and subsequent flame spread of solid fuels (PBAA, PIB and paraffin waxes), in a hot oxidizing gas stream were studied experimentally by using a shock tunnel with a flat-plate fuel specimen placed parallel to the flow. Effects of freestream oxygen content (20% - 100%), freestream temperature (1270 - 2100 K), freestream velocity (77-275 m/sec) and diluent inert gases (N_2, Ar) on ignition and flame spread behavior were studied. It was observed that, if the external heating rate is high or if the sample tends to pyrolyze at low temperatures, the heat feedback from the exothermic gas phase reaction is not important and the effects of freestream oxygen content are small for both ignition and flame spread. However, if the external heating rate is small or the sample tends to pyrolyze only at high temperatures, the heat feedback from the exothermic gas phase reaction is important and effects of free-stream oxygen content are significant for ignition and flame spread.

Based on work performed under Grant AF74-2602 sponsored by the Energetics Division, Air Force Office of Scientific Research.

Accession No. A75-35494. Available from AIAA.

"PHYSICS OF FLAME"

Irvin Glassman, William A. Sirignano, Martin Summerfield

Aerospace and Mechanical Sciences Report No. 952, Sept., 1970, Princeton University, Princeton, N.J.

Theoretical and experimental analyses of flame spreading across pools of liquid fuels and the ignitability of such pool under quiescent and flowing environments are presented. The fundamental concept is that, when the temperature of the liquid fuel is below the flash point, convection currents in the liquid play a dominant role in both ignitability and flame spreading. These currents are induced by either or both surface tension and buoyancy forces. A theoretical analyses related to ignition of fuels by projectiles is presented. A brief section on the combustion of nitrocellulose-base propellants is included.

Based on work performed under contract DAAD05-68-C-0450 and monitored by the Ballistic Research Laboratories.

Accession No. AD-718866 - Available from NTIS.

"A STUDY OF SOME FACTORS INFLUENCING THE IGNITION OF A LIQUID FUEL POOL"

R. J. Murad, J. Lamendola, H. Isoda and M. Summerfield

Combustion and Flame, Vol. 15, No. 3, Dec. 1970, pp. 289-298.

Two particular problems concerning the ignitability of a pool of liquid fuel are considered. First is the problem of defining the domain of ignitability of a pool of fuel at a superflash temperature subjected to a cross wind. It is postulated that this domain is bounded by the lean mixture limit or by the blowoff limit of the local fuel-air mixture, whichever is encountered first above the surface. This domain is calculated for a laminar boundary layer over a flat pool of fuel. The agreement between this predicted boundary and the boundary found here experimentally is generally quite good.

Second is the problem of determining what factors control the ignitability of a liquid pool of fuel at a subflash temperature. The heating of such a pool to the point of ignition, by an energy source in the space above it, is retarded considerably by motion induced in the pool. Suppression of the motion enhances the ignitability markedly. The induced motion produces a vortex cell whose size depends on various fuel and igniter parameters. The driving force causing this fluid motion is postulated to be a combination of the forces resulting from buoyancy in the pool and surface tension gradient on the surface.

Based on work performed under contract DAAD05-68-C-0450 issued by the Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland.

Accession No. A71-19245 - Available from AIAA.

"PRE-IGNITION MOTION OF LIQUID FUELS DUE TO LOCAL HEAT INPUT AT THE UPPER SURFACE."

Bruce W. MacDonald, E. G. Plett and Martin Summerfield

Aerospace and Mechanical Sciences Report No. 1050, Sept. 1972, Princeton University, Princeton, N.J.

When a liquid fuel is subjected to thermal stress at a boundary, several interconnected phenomena occur which can critically affect the ignition event. Through the mechanisms of liquid buoyancy and surface tension variation with temperature, convection under certain circumstances is induced in the liquid by the thermal stress. The degree to which the concentrated heat is dispersed away from its input locus via convection governs the development of the fuel temperature profile with time and thus its ignition behavior. Greater understanding of fuel pre-ignition motion is thus important in understanding liquid fuel ignition. Previous experimental work by Murad et al. showed that ignition delay times were modified by varying the surface tension and viscosity behavior of several fuels. This study extends the work of Murad by using a more rigorous analytical model of the physical situation and by investigating additional experimental conditions. The pre-ignition motion of decane and water under a variety of conditions was observed and photographed. A system of equations in two dimensions describing these experimental conditions was developed and solved numerically on a digital computer. The behavior of decane, heptane, methyl alcohol, water, molten aluminum and molten potassium nitrate were all predicted by this model under a variety of conditions, including those imposed experimentally on decane, methyl alcohol, and water. Good qualitative and fair quantitative agreement was obtained between theory and experiment for the liquid fuels that were tested. Both approaches provide quantitative evidence that the surface tension mechanism strongly dominates the pre-ignition behavior both for pools of fuel heated from above and for other liquids as well. Buoyancy effects only become significant after several minutes, generally outside any pre-ignition interval of interest.

Based on work performed partially under contract DAAD05-68-0450 and monitored by the Ballistic Research Laboratories.

Available through interlibrary loan.

"THEORY OF PROPELLANT IGNITION BY HETEROGENEOUS REACTION"

C. H. Waldman and M. Summerfield

AIAA Journal, Vol. 7, No. 7, July 1969, pp. 1359-1361.

This paper offers a theoretical solution for the problem of predicting the ignition delay when a condensed fuel (solid or liquid) is brought suddenly in contact with a hot reactive gas, on the assumption that the initiating exothermic reaction is a heterogeneous one right on the fuel surface. Previous publications have dealt with the theory of ignition on the assumption of a different mechanism, that the initiating reaction takes place in the thin vapor boundary layer after initial vaporization caused by the heat-up of the fuel surface.

Considering the semiquantitative nature of the two theoretical approaches the conclusion that can be drawn is that the two theories produce similar predictions. That is, each one predicts that the ignition delay is roughly inversely proportional to the partial pressure of oxygen in the test gas, and each one predicts that when the total pressure is augmented by the addition of a nonoxidizing neutral gas, the ignition delay is shortened, simply because the denser gas heats the fuel surface more intensely.

Based on work performed under Contract AF49(638)-1267 sponsored by the Air Force Office of Scientific Research.

Accession No. A69-41897# - Available from AIAA.

"SOLID PROPELLANT FLAMMABILITY INCLUDING IGNITABILITY AND COMBUSTION LIMITS"

L. H. Caveny, M. Summerfield, R. C. Strittmater and A. W. Barrows

Proceedings of 10th JANNAF Combustion Meeting, Aug. 1973, Newport, R.I. CPIA Pub. 243, Vol. III, Dec. 1974, pp. 133-156.

Studies were directed at developing an understanding of mechanisms of propellants burning in air and of factors that control limits of burning so that one may rationalize choices of propellant formulation, charge configuration, process techniques, and special additives to reduce accidental ignition and burning of propellants in ambient air. Propellants were categorized in terms of convective, conductive, and radiative ignition data and in terms of burning rate and extinguishment limit data. The flammability of AP and HMX composite propellants is greatly increased by the presence of air; generally double base propellants are more flammable than the composite propellants, both in N_2 and air. Three types of additives for reducing flammability were evaluated: coolants (e.g., oxamide), char formers (e.g., phosphates), and flame inhibitors (e.g., halogen compounds). No practical success has been achieved with char formers and flame inhibitors. Significant increases in the flammability limits have been achieved using coolants (at the 10% level) with composite propellants made from high decomposition temperature ingredients (e.g., HMX and polyurethane).

Based on work performed under Contract DAAD05-72-C-0135 sponsored by the U.S. Army.

Available only from CPIA.
This material will be the subject of a report issued by the U.S. Army's Ballistic Research Laboratories.

"EVALUATION OF ADDITIVES TO REDUCE SOLID PROPELLANT FLAMMABILITY IN AMBIENT AIR"

Leonard H. Caveny, Anthony Z. Mackiewicz and Martin Summerfield

BRL Contract Report No. 278, Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, December 1975.

An experimental investigation to obtain an understanding of how chemical additives (i.e., flame inhibitors, char formers, and coolants) intended to reduce the likelihood of accidental ignition and flammability affect the combustion of high energy propellants in ambient air. Several composite propellants were made more resistant to ignition. However, test results for high energy propellants revealed that (once ignition occurred) the continual resupply of reactants (both air and propellant products) overwhelms the contributions of the additives and prevents self-extinguishment in ambient air. In some cases elimination of the conventional external flame resulted in smoldering which produced extremely hazardous, explosive gases. The investigation revealed the following encouraging trends. Several low energy materials (i.e., impetus less than 200,000 ft-lb/lb) suitable for outer-layer protective coatings appear to be promising with respect to their ability to self-extinguish and to be resistant to ignition under ambient conditions. Several of the moderately high energy nitramine composite propellants with high decomposition temperature binders are several times more resistant to accdiental ignition than conventional propellants and are easily extinguished, if ignited.

Based on work performed under sponsorship of the U.S. Army under Contract DAAD05-72-C0135.

Accession No. AD-A019108. Available from NTIS.

IV POROUS PROPELLANTS

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"THEORY OF FLAME FRONT PROPAGATION IN POROUS PROPELLANT CHARGES UNDER CONFINEMENT"

K. K. Kuo, R. Vichnevetsky and M. Summerfield

Aerospace and Mechanical Sciences Report No. 1000, Princeton University, Princeton, N.J., August 1971.

Ultra-high burning rates can be achieved by combustion of porous media. A theoretical model is developed to describe the flame propagation in a packed bed of granular propellant. The calculated pressure-time-distance transients, wave propagation speed, and mass fraction of propellant burned during flame propagation, all agree well with experimental data obtained for the same conditions. Results demonstrate that the combustion-generated strong pressure gradient causes the hot product gas to deeply penetrate the unburned region. A continental divide forms automatically in the pressure distribution as the wave progresses into the charge. In the particular case studied, after traversing a distance of 3 cm, the flame front reaches a speed about 5000 times the normal propellant burning rate and continues to accelerate as the internal pressure increases.

Based on work performed under Contract N00014-67-A-0151-0023 issued by the Office of Naval Research.

Accession No. AD762063 - Available from NTIS.

"THEORY OF FLAME FRONT PROPAGATION IN POROUS PROPELLANT CHARGES UNDER CONFINEMENT"

K. K. Kuo, R. Vichnevetsky and M. Summerfield

AIAA Journal, Vol. 11, No. 4, April 1973, pp. 444-451.

Ultra-high burning rates can be achieved by combustion of porous media. A theoretical model is developed to describe the flame propagation in a packed bed of granular propellant. The calculated pressure-time-distance transients, wave propagation speed, and mass fraction of propellant burned during flame propagation, all agree well with experimental data obtained for the same conditions. Results demonstrate that the combustion-generated strong pressure gradient causes the hot product gas to deeply penetrate the unburned region. A continental divide forms automatically in the pressure distribution as the wave progresses into the charge. In the particular case studied, after traversing a distance of 3 cm, the flame front reaches a speed about 5000 times the normal propellant burning rate and continues to accelerate as the internal pressure increases.

Based on work performed in part under Contract N00014-67-A-0151-0023 issued by the Power Branch of the Office of Naval Research.

Accession No. A71-18646# - Available from AIAA. Accession number identifies AIAA Paper 71-210 which is superseded by the article cited above.

"THEORY OF STEADY-STATE BURNING OF POROUS PROPELLANTS BY MEANS OF A GAS-PENETRATIVE MECHANISM"

K. K. Kuo and M. Summerfield

AIAA Journal, Vol. 12, No. 1, Jan. 1974, pp. 49-56.

High speed flame propagation well above the normal deflagration rate can be achieved in the burning of porous propellants. Gas-penetrative burning of porous propellants under strong confinement is inherently self-accelerating. However, under suitable physical conditions, a constant-speed combustion wave can be produced. The jump conditions and the equivalent Rankine-Hugoniot relation for porous propellant burning are derived. An important result is that, whereas the usual R-H relation forbids the existence of a steady-state combustion wave that has both a pressure rise and a density decrease (called forbidden region on the R-H curve), this restriction can be bypassed in the situation discussed here, and high-speed compressive-expansive waves are legitimate solutions of the equations. It is shown also that the structure of the wave and its speed of propagation are affected by propellant porosity, ignition temperature, specific burning area, gas permeability and pressure. The flame propagation speed is determined as the eigenvalue of this two-point boundary value problem.

Based on work performed under Contract N00014-67-A-0151-0023 sponsored by the Power Branch of the Office of Naval Research.

Journal Article supersedes AIAA Paper No. 73-221 (Accession No. A73-17663# - Available from AIAA), January1973.

"HIGH SPEED COMBUSTION OF MOBILE GRANULAR SOLID PROPELLANTS: WAVE STRUCTURE AND THE EQUIVALENT RANKINE-HUGONIOT RELATION"

K. K. Kuo and M. Summerfield

Proceedings of 15th Symposium (International) on Combustion, 1974, pp.

This research was stimulated mainly by the great potential of granular propellants in achieving unusually high gasification rates and producing high thrusts after a short initial period of transient burning. Physically, the high burning speeds of gas-permeable propellants are caused by the penetration of hot product gases into the unburned portion. The strong convective heat feedback from the burned products to the unburned medium augments the speed of flame propagation by two to three orders of magnitude above the normal deflagration rate of cast solid propellants. The results of the analytical mode reveal interesting features of the computed wave structure: (a) the pressure distribution displays a hump in the combustion wave, gas flowing in opposite directions from the peak; (b) the pressure gradient has its highest value at the ablation front and the relative velocity between particle and gas also reaches a maximum value there; (c) the wave thickness and shape strongly depend upon the geometric factors including fractional porosity, specific burning surface, and gas-permeability of the propellant charge. From the study of the equivalent Rankine-Hugoniot relation, it is found that the origin of the equivalent Hugoniot curve is shifted to a much higher pressure level due to the transmission of normal stress in the non-fluidized section of the granular propellant. This shift of origin in the R-H diagram significantly enlarges the allowed region for real burning rates. This explains why it is possible to attain extremely high burning speeds (on the order of thousands of cm per second) by using granular propellants, and how one can enter the "forbidden" speed range of the usual R-H diagram by burning gas-permeable propellants. It is proved mathematically that all the conventional R-H properties are preserved when the new origin, based upon the apparent pressure and apparent density, is used. It is also shown that the generally observed gas-penetrative burning of a granular propellant lies on the deflagration branch of the equivalent R-H curve, and the flame speed is the eigenvalue of the two-point boundary value problem.

Based on work performed under contract N00014-67-A-0151-0023 issued by the Power Branch of the Office of Naval Research.

Available through your local library system.

"AN EXPERIMENTAL STUDY OF PRESSURE WAVE PROPAGATION IN GRANULAR PROPELLANT BEDS."

A. C. Alkidas, S. O. Morris, L. H. Caveny and M. Summerfield

AIAA Journal, Vol. 14, No. 6, June 1976, pp. 789-792.

The ignition transients and penetrative burning characteristics of confined granular propellant beds in a cylindrical tube (loading densities up to 1.03 g/cm^3 and pressures up to 4000 bar) were investigated to test the 1-D pressure-wave propagation profiles predicted by the 1971 Kuo-Vichnevetsky-Summerfield analytical model. Thus, it was found that following the initial pressure rise along the bed, the position of peak pressure occurs within the bed and progresses downstream at an accelerating rate. The ignition time of the granular bed increases sharply with decreasing loading density. However, the pressurization time depends primarily on the diameter and burning rate of the granules that make up the bed. Wall friction acting on the unburned propellant along the tube attenuates downstream transmission of solid phase pressure generated by the upstream burning processes. This work has applications to the internal ballistics of guns, deflagration to detonation transition, and fast burning rocket charges.

Based on work performed under sponsorship of the Power Branch of the Office of Naval Research under contract N00014-67-A-0151-0023.

Journal article supercedes AIAA Paper No. 75-242, January 1975. Accession No. A75-20292 for AIAA Paper No. 75-242. Available from AIAA.

V SOLID ROCKET MOTORS

V Solid Rocket Motors

A. Ignition Transients

B. Performance Predictions

V SOLID ROCKET MOTORS

V SOLID ROCKET MOTORS

"THRUST TRANSIENT PREDICTION AND CONTROL OF SOLID ROCKET ENGINES"

W. J. Most, B. W. MacDonald, P. L. Stang and M. Summerfield

WSCI Paper 68-33, The Combustion Institute, October 1968.

The research reported in this paper is directed toward the development of an analytical model for predicting the thrust-time curve during the entire ignition transient of a solid propellant motor. This model characterizes the local ignition event by a constant critical surface ignition temperature and by including a surface heat release term to account for exothermic decomposition below the critical temperature. Flame spreading is described by coupling this ignition model with an empirical description of the gas phase heat convection to the propellant grain. The propellant burning rate after ignition is achieved is taken as the steady state burning rate. The model is completed by writing the dynamic energy and continuity equations. This model is compared to others appearing in the literature.

The theoretical predictions of the model are compared to experimental test firings of a two-dimensional rocket motor and of motors with more realistic grain configurations. An extensive range of igniter system and engine design parameters are covered. Both aluminized and unaluminized propellants are considered and shown to be similar. The abrupt shift from a vigorous, well-ignited rocket motor to an extended hangfire or misfire can be caused by small changes in igniter design parameters. This sensitivity is predicted theoretically and demonstrated experimentally.

This paper concludes that a physically rational theory has been developed that can predict the entire motor ignition transient for motors with head-end pyrogen igniters. This is verified experimentally.

Based on work performed under NASA Grant NGR-31-001-109 supervised by Langley Research Center.

Accession No. A69-18365*# - Available from AIAA.

V. A.
Rocket Motors
- Ignition Transients

"STARTING THRUST TRANSIENTS OF SOLID ROCKET ENGINES"

W. J. Most and M. Summerfield

Aerospace and Mechanical Sciences Report No. 873, July 1969,
Princeton University, Princeton, N.J.

In the past, the design engineer has been forced to rely on empirical and statistical knowledge of previous firings in order to design the ignition system of a solid rocket motor or to predict the starting delay time of a given rocket-igniter system. In order to predict the entire ignition transient analytically, the processes of local ignition, heat transfer and subsequent flame propagation and the gas dynamics of the combustion chamber must all be described quantitatively. Each of these elements has been the focus of extensive research in itself. The purpose of this paper is to present the results of these research efforts, in our laboratory and elsewhere, in relation to the objective of predicting analytically the entire ignition transient.

A particular analytical model, developed for the class of engines with large port-to-throat area ratios and head-end mounted pyrogen igniters, is presented. This model characterizes the local ignition event by ascribing to the propellant a critical surface temperature for ignition and by including a surface heat release term to account for exothermic decomposition while the surface is still below the critical temperature. Flame spreading is described by coupling this ignition model with a general description of the heat transfer from the gas phase to the unignited propellant grain. Any propellant burning rate law, steady or nonsteady, can be used once ignition has been achieved. The model is completed by the dynamic energy and continuity equations for the motor free volume. This particular model is compared to others which have appeared in the literature, with special attention paid to those reports in which comparisons between theoretical predictions and experimental test firings are offered.

The limitations of the various models are examined, especially with regard to those particular assumptions which cannot be justified experimentally. The applicability of the various models for the prediction of marginal (hangfire) situations is examined.

This paper concludes that the analytical models now available can provide useful predictions of the entire ignition transient, at least for the class of motors for which they have been developed, and this has been verified experimentally.

Based on work performed under Grant NGR 31-001-109 sponsored by the Office of Advanced Research and Technology, NASA, supervised by Langley Research Center.

Accession No. N72-75433 - Available from NTIS.

"COMBUSTION ANOMALIES IN STOP-RESTART FIRING OF HYBRID ROCKET ENGINES"

M. A. Saraniero, L. H. Caveny and M. Summerfield

Aerospace and Mechanical Science Report No. 945, Sept. 1970, Princeton University, Princeton, N.J.

An experimental investigation of the restart process of an oxygen-Plexiglas hybrid rocket demonstrated that preheating the fuel (as a consequence of a previous ignition and a temporary extinguishment) significantly increases the rate of chamber pressurization and produces regression rate overshoots during reignition. Higher rates of chamber pressurization measured during the restart transient imply faster instantaneous regression rates of the fuel during restart. Transient periods following the initial ignition and the restart after a two-second shut-down were observed for four experimental tests which were conducted at two oxidizer flow rates, 0.078 lbm/sec and 0.039 lbm/sec, and two chamber pressures, 80 psig and 320 psig. Thermocouples made from 0.001 inch diameter chromelalumel wire were embedded in the fuel to record subsurface temperature histories.

A mathematical model of the thermal processes in the fuel and the events that occur during an experimental firing was developed to calculate the regression rate transients. Quantitative agreement with experimental results was obtained by making nominal corrections to the calculated convective and radiative heating rates. A parametric study investigated the influence of the fuel's thermal characteristics (thermal conductivity, surface temperature, and heat of gasification) and the shut-down duration on the transient responses. The calculated results showed that instantaneous regression rate overshoots were as high as 29% when high energy fuels are reignited.

The results of this study indicate that the transient behaviors of pressure and regression rate during reignition after shut-down (the duration of which has been varied over a range of 0.9 to 4.0 sec) can be anticipated and predicted once the regression characteristics of individual fuel/oxidizer combinations have been established. Thus, extensive experimental firings of full scale rocket motors will not be required to adequately predict pressure-time histories and fuel consumption following reignition if proper attention is given to understanding the thermal distributions during shut-down periods.

Based on work performed under Contract NGR-31-001-109 issued by Office of Advanced Research and Technology, NASA.

Accession No. N72-26960 - Available from NTIS.

V. A.
Rocket Motors
- Ignition Transients

"RESTART TRANSIENTS OF HYBRID ROCKET ENGINES"

M. A. Saraniero, L. H. Caveny and M. Summerfield

Journal of Spacecraft and Rockets, Vol. 10, No. 3, March 1973, pp 215-217.

The problems associated with restarting hybrid rocket motors (i.e., rocket motors wherein a liquid or gaseous oxidizer is injected into the port of a solid fuel grain with subsequent mixing and combustion of the oxidizer and fuel) following a brief period of extinguishment were investigated experimentally. In the extreme, reignition and re-establishment of the oxidizer flow of a briefly extinguished hybrid motor which is heated in depth and undergoing subsurface reactions will produce catastrophic increases in burning rate. If a precise p_{ch} vs t program is required, results demonstrate that the designer must carefully program the external ignition stimulus and oxidizer flow rate during the restart ignition period by taking into consideration at least three factors: (1) pressure prior to extinguishment, (2) duration of shutdown interval, and (3) desired pressure following restart. The measured pressure vs time traces explicitly show the extent to which restart ignition differs from the first ignition. Increasing m_O greatly reduces the t_9 on reignition. The time to achieve 90% of the operating pressure t_9 is reduced by as much as 88%, and the time to achieve ignition is reduced by as much as 45%. Also the measured pressure time traces reveal that there is no appreciable increase in burning rate after the thermal profile is fully established. This indicates that the specific energy (approximately 350 cal/g) required to gasify PMM is much larger than the specific energy increase attributed to indepth absorption of thermal radiation (30 cal/g) during the time interval of the test.

Based on work performed under sponsorship by NASA's Office of Advanced Research and Technology under Grant NGL-31-001-109 and monitored by the Applied Rocket Research Section of the NASA Langley Research Center.

Accession No. A73-26669# - Available from AIAA.

"THE STARTING TRANSIENT OF SOLID-PROPELLANT ROCKET MOTORS WITH HIGH INTERNAL GAS VELOCITIES"

A. Peretz, L. H. Caveny, K. K. Kuo and M. Summerfield

Aerospace and Mechanical Science Report No. 1100, April 1973, Princeton University, Princeton, N.J.

A comprehensive analytical model which considers time and space development of the flow field in solid propellant rocket motors with high volumetric loading density is described. The gas dynamics in the motor chamber is governed by a set of hyperbolic partial differential equations, that are coupled with the ignition and flame spreading events, and with the axial variation of mass addition. The flame spreading rate is calculated by successive heating-to-ignition along the propellant surface. Experimental diagnostic studies have been performed with a rectangular window motor (50 cm grain length, 5 cm burning perimeter and 1 cm hydraulic port diameter), using a controllable head-end gaseous igniter. Tests were conducted with AP composite propellant at port-to-throat area ratios of 2.0, 1.5, 1.2, and 1.06, and head-end pressures from 35 to 70 atm. Calculated pressure transients and flame spreading rates are in very good agreement with those measured in the experimental system.

Based on work performed under Research Grant NGL-31-001-109 sponsored by the Office of Advanced Research and Technology, NASA.

Accession No. N74-13506. Available from NTIS.

"THRUST TRANSIENTS OF LARGE SOLID ROCKET MOTORS"

Leonard H. Caveny, Arie Peretz and Martin Summerfield

Proceedings of the 10th JANNAF Combustion Meeting, Aug. 1973 at Newport, R. I. CPIA Pub. 243, Vol. I, Dec. 1974, pp. 21-44.

An analytical model which considers time and space development of the flow field in solid-propellant rocket motors with high volumetric loading density was used to predict the ignition characteristics of larger solid rocket motors (e.g., thrust > 2 × 10^6 lb and length > 100 ft). Uncertainties associated with the prediction of peak pressures are attributed largely to incomplete knowledge of erosive burning. The calculated results demonstrate that the flow field from large solid propellant motor grains overpower the uncertainties associated with the detailed ignition processes. Sensitivity analyses revealed that the ignition and pressurization times were not appreciably affected by the expected variations in motor parameters, if the pyrogen produced sufficiently high convective heating rates. Accordingly, small (< 0.1% of total motor weight) head-end mounted pyrogens which promote a rapid onset of flame spreading are expected to produce rapid and reproducible chamber pressurization.

Based on work performed under NASA Grant NGL 31-001-109 monitored by NASA Langley Research Center and the Jet Propulsion Laboratory of the California Institute of Technology.

Available only from CPIA.

"THE STARTING TRANSIENT OF SOLID PROPELLANT ROCKET MOTORS WITH HIGH INTERNAL GAS VELOCITIES"

A. Peretz, K. K. Kuo, L. H. Caveny and M. Summerfield

AIAA Journal, Vol. 11, No. 12, Dec. 1973, pp. 1719-1727.

A comprehensive analytical model which considers time and space development of the flow field in solid-propellant rocket motors with high volumetric loading density is described. The gas dynamics in the motor chamber is governed by a set of hyperbolic partial differential equations, that are coupled with the ignition and flame spreading events, and with the axial variation of mass addition. The flame spreading rate is calculated by successive heating-to-ignition along the propellant surface. Experimental diagnostic studies have been performed with a rectangular window motor (50 cm grain length, 5 cm burning perimeter and 1 cm hydraulic port diameter), using a controllable head-end gaseous igniter. Tests were conducted with AP composite propellant at port-to-throat area ratios of 2.0, 1.5, 1.2, and 1.06, and head-end pressures from 35 to 70 atm. Calculated pressure transients and flame spreading rates are in very good agreement with those measured in the experimental system.

Based on work performed under NASA Grant NGL-31-001-109 monitored by NASA Langley Research Center and the Jet Propulsion Laboratory of the California Institute of Technology.

The above cited article supersedes AIAA Paper 72-1119. Available from AIAA as Accession No. A73-14909.

"MICRO ROCKET IMPULSIVE THRUSTERS"

Leonard H. Caveny and Martin Summerfield

Aerospace and Mechanical Science Report No. 1014, Nov. 1971, Princeton University, Princeton, N.J.

Light weight solid propellant motors which supply high thrusts (>500 lbf) for durations on the order 0.010 sec. (referred to as impulsive thrusters) require special analysis of items such as internal ballistics, propellant combustion, ignition stimuli, exhaust plume envelope, and inert hardware. An almost explosive ignition and pressurization coupled with the requirements for reproducible thrust versus time programs are analyzed by a mathematical model that emphasizes gas flow and propellant combustion dynamics. Studies were directed at analyzing a center-vented motor approximately 7 inches long and 0.3 inches in diameter with a total impulse of 3.6 lbf-sec and a web time of 0.006 sec. A survey of the rocket motor concepts revealed that the desired thrust versus time program can be achieved by internal burning grains and existing high burning rate composite propellants. Limitations were placed on volumetric loading density as a result of uncertainties of how the center-vented flow affects thrust vector alignment and nozzle flow losses. The mathematical model for transient internal ballistics developed during the study can be applied to a wide range of high performance rocket motors which experience rapid ignition and pressurization transients.

Performed under Contract No. DAHC-60-71-C-0034 issued by the U.S. Army Advanced Ballistic Missile Defense Agency.

Accession No. AD735381 - Available from NTIS.

"SOLID PROPELLANT MICROMOTORS AND IMPULSIVE THRUSTERS"

Leonard H. Caveny and Martin Summerfield

Paper No. 710766, Sept., 1971, Society of Automotive Engineers

Light weight solid propellant motors which supply high thrusts (>500 lbf) for durations on the order 0.010 sec. (referred to as impulsive thrusters) require special analysis of items such as internal ballistics, propellant combustion, ignition stimuli, and inert hardware. An almost explosive ignition and pressurization coupled with the requirements for reproducible thrust versus time programs are analyzed by a mathematical model that emphasizes gas flow and propellant combustion dynamics. To further reduce impulsive thruster operating times, limitations in propellant burning rate must be circumvented by departures from conventional internal burning, thin propellant web motor designs. A novel approach that uses a dense, porous propellant is described in terms of a recently developed combustion theory for porous propellants.

Based on work performed under Contract No. DAHC 60-71-C-0034 issued by the U.S. Army Ballistic Missile Defense Agency.

SAE Paper No. 710766 - Available from SAE, Two Pennsylvania Plaza, New York, New York 10001.

"PRESSURE TRANSIENTS OF SOLID ROCKETS WITH SLOW GAS PHASE REACTION TIMES"

L. H. Caveny, R. A. Battista and M. Summerfield

AIAA Paper No. 73-1301, Nov. 1973, New York: American Institute of Aeronautics and Astronautics.

Propellant and combustion chamber combinations with flame-zone reaction times (τ_f) that are an appreciable fraction of the chamber gas residence times experience erratic ignition, uncontrolled pressure drifts, and low I_{sp} efficiencies. Propellants likely to produce these problems in the normal L* range include double base propellants, which may have dark zone τ_f's up to 5 msec, and propellants that produce Al_2O_3/Al agglomerates that burn beyond the propellant surface. For example, L* values greater than 1000 cm were required to achieve stable operation of an NC/MTN propellant at 34 atm; adding 10% ammonium perchlorate to the propellant eliminated the dark zone and reduced the stable L* to 40 cm. Catalysts (e.g., lead salicylate) which doubled burning rate but did not decrease τ_f improved stability only slightly. A transient internal ballistics analysis using τ_f data (to account for the incompleteness of the gas phase reactions within the chamber) explained motor data and predicted stable operating domains. Motor stability increases with increasing pressure, L*, burning rate, and duration of choked igniter flow and with decreasing pressure and temperature sensitivity of burning rate.

Based on work performed under contract AF69-1651 from the Energetics Division, Air Force Office of Scientific Research.

Accession No. A74-12946. Can be ordered from AIAA.

"EROSIVE BURNING OF NONMETALLIZED COMPOSITE PROPELLANTS - DATA ACQUISITION AND ANALYSIS"

Benjamin B. Stokes, Robert O. Hessler, and Leonard H. Caveny

To appear in Proceedings of 13th JANNAF Combustion Conference, September 1976.

A 50 cm long slab motor with two closely spaced propellant surfaces (e.g., 0.7 cm apart) was used to obtain erosive burning data. The motor was extinguished by liquid quench during the early part of motor operation. Static pressure was measured at 5 axial stations and distance burned was measured directly from the extinguished propellant surfaces. Test results for three nonmetallized AP composite propellants are presented. The data were correlated by using the Lenoir-Robillard equation to deduce the burning rates which produced the best agreement between measured and calculated pressures.

Based on work performed under sponsorship of the Air Force Office of Scientific Research as part of Grant AF-74-2602 and under sponsorship of Thiokol Corp./Huntsville Division.

VI METAL EROSION

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"EROSIVE EFFECTS OF COMBUSTION GASES ON METALLIC COMBUSTION CHAMBERS"

Edelbert G. Plett and Martin Summerfield

Final Report (Part I) on Contract DAAA 25-71-C0109; Guggenheim Laboratories, Dept. of Aerospace and Mechanical Sciences, Princeton University, Princeton, N.J., August 1972.

The erosive effects of combustion gases on metallic combustion chambers has been investigated. Particular attention has been directed toward obtaining an understanding of the severe erosion of aluminum alloys when a gas path is provided for the combustion gases to escape through the sample of the chamber material. An analytical model was constructed which considered the heat transfer from the hot products of the propellant combustion to be the source of heat causing melting and erosion. By comparing experimental results with numerical results obtained using this model, it was concluded that the onset of erosion occurs when the surface temperature of the alloy reaches its melting point. Aluminum alloys reach this point somewhat earlier than brass due to their lower solidus or melting point, and less favourable thermal properties. At low pressures, (below 20,000 psi), erosion of the primary wall material is largely due to continued heating by the hot products of combustion. As the pressure is increased, erosion is augmented, in the case of aluminum and titanium, by additional exothermal chemical reactions believed to be between the eroded metal and the oxide carrying radicals in the combustion products. The nature and extent of these reactions needs to be established.

Simulated secondary support structures, made of steel or brass, placed in the path of the hot gases escaping through an eroding hole in aluminum are observed to erode much more severely than if the samples were subjected directly to the flow of propellant combustion products. This is believed to be due to the additional heat released by the oxidation of eroded aluminum. Further investigation of this phenomenon is required.

Thin metallic layers of brass and steel bonded or held in place on the inside of samples of wall material, consisting primarily of aluminum, reduced the severety of erosion on the aluminum. A thin layer of rubber on the inside of an aluminum sample proved to be even more effective in reducing erosion. Further study is required to optimize methods of prevention of erosion of primary wall materials made of aluminum and secondary support structures made of steel or other metal alloys.

Based on work performed under Contract DAAA 25-71-C0109 issued by the U.S. Army, Frankford Arsenal, Philadelphia, Pa.

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"EROSIVE EFFECTS OF COMBUSTION GASES ON METALLIC COMBUSTION CHAMBERS"

Edelbert G. Plett, Ross E. Shrader and Martin Summerfield

Final Report (Part II) on Contract DAA25-71-C0109; Guggenheim Laboratories, Dept. of Aerospace & Mechanical Sciences, Princeton University, Princeton, N.J., October 1972.

The erosive effects of combustion gases on metallic combustion chambers have been investigated. The understanding that was reported in Part I of this report has been developed further, with additional experiments and refined and extended theoretical developments.

Calculations of the effect of chemical reactions, in the boundary layer or on the surface, verify that the heat produced by the oxidation of aluminum can account for the energy required to melt the excess metal which is not predicted to be melted by inert heating from the propellant products.

Experiments conducted with several aluminum alloys and a number of different propellants, with isochoric flame temperatures ranging from 2197 to 3000°K, demonstrated again that the onset of erosion corresponds to the onset of melting of the aluminum. Lower concentrations of CO_2 and H_2O were found to occur in HMX propellants and erosion data showed considerably lower excess erosion with these propellants. Synergistic erosion of steel was also substantially reduced by the use of HMX propellant compared with the more commonly used IMR propellant.

A spectrograph and a residue catcher and analysis technique was used respectively to demonstrate that propellant products oxidize the eroding aluminum and that the metal is molten when removed from the surface.

Based on work performed under Contract DAAA25-71-C0109 issued by the U. S. Army, Frankford Arsenal, Philadelphia, Pa.

Accession No. AD774326. Available from NTIS.

"THE ALUMINUM BURNTHROUGH PROBLEM: POTENTIAL SOLUTIONS"

M. Summerfield, A. M. Varney, E. G. Plett, R. E. Shrader, A. Alkidas and S. O. Morris

Proceedings of the 1973 JANNAF Propulsion Meeting, Vol. I, CPIA Publication 242, September 1973, pp. 641-664.

Basic and applied research is brought to bear on the technical barrier that has precluded the use of aluminum in high pressure propellant combustion chambers; namely, burnthrough. This paper summarizes the practical solutions which have evolved from a more detailed basic understanding of the mechanisms involved in burnthrough. (More details of the scientific aspects of this work are given in the Proceedings of the 10th JANNAF Combustion Conference, 1973.) Possible solutions include use of (a) a plastic or rubber liner, (b) cool and/or low oxidizing propellant, (c) powder metallurgy aluminum alloys, (d) inner cladding of steel, copper or SAP/PMA, or (e) a thick anodic coat on the inner surface.

Based on work performed under Contract DAAG46-72-C-0078 issued by the U.S. Army Materials and Mechanics Research Center, Watertown, Mass., with funding provided by the Small Arms Systems Agency and including data drawn from an earlier contract with Frankford Arsenal.

Accession No. AD527660 - Distribution Controlled - Not available from DDC - Available only from CPIA.

"EROSION OF METALS BY HIGH PRESSURE COMBUSTION GASES: INERT AND REACTIVE EROSION."

E. G. Plett, A. C. Alkidas, R. E. Shrader and M. Summerfield

ASME Journal of Heat Transfer, February 1975, pp. 110-115.

An experimental and theoretical investigation of the erosion of various metals by high temperature, high pressure flows of combustion gases is described. The erosion process was categorized as either inert or a combination of inert and reactive erosion. Experimental results indicated the existence of two thresholds, the first represents the onset of erosion and the second the transition from purely inert to inert plus reactive erosion. Inert erosion was modeled by means of the melt and wipe-off theory. Experimental results are presented to demonstrate various erosion regimes and to identify the conditions for inert and reactive erosion.

Based on work performed under contract DAAG46-72-C-0078 issued by the U.S. Army Materials and Mechanics Research Center, Watertown, Mass., and under contract DAAA-25-71-C0109, issued by the U.S. Army, Frankford Arsenal, Philadelphia, Pa.

Journal article supersedes ASME Paper 75-HT-M (Accession No. A75-23278 - available from AIAA).

"EROSION OF POWDER METALLURGY ALUMINUM ALLOYS BY HOT PROPELLANT GASES"

A. C. Alkidas, A. M. Varney, R. E. Shrader, S. O. Morris and M. Summerfield

ASME Publication, Paper No. 76-Mat L, submitted to ASME Journal of Engineering Materials and Technology, September 1975.

Experimental results are presented on the erosion of PMA (Powder Metallurgy Aluminum) alloys by a pulse of high pressure and high temperature combustible gases. The PMA alloys have been found to exhibit superior erosion resistance characteristics than wrought aluminum alloys. Of the PMA alloys tested, SAP materials (Sintered Aluminum Powder) were shown to be the best. The primary mechanism of the erosion of PMA alloys was found to be the melt and wipe off process. Combustion of aluminum that is responsible for the catastrophic erosion of wrought aluminum alloys was inhibited in PMA tests. Several hypotheses that explain erosion resistance of the PMA alloys have been postulated.

Based on work performed under sponsorship of the U.S. Army Materials and Mechanics Research Center, Watertown, Mass. under Contract DAAG46-72-C-0078.

Available from Engineering Societies Library, New York, N.Y. as ASME Paper 76-MatL.

"EROSIVE EFFECTS OF VARIOUS PURE AND COMBUSTION-GENERATED GASES ON METALS, PART I"

A. C. Alkidas, S. O. Morris and M. Summerfield

Report AMMRC CTR 75-23, Army Materials and Mechanics Research Center, Watertown, Mass., October 1975.

This study presents an experimental investigation of the thermal and chemical erosion characteristics of steel alloys under the short exposure of high pressure and high temperature propellant gases (vented-combustor apparatus) and pure gases (ballistic compressor apparatus). In the vented-combustor tests, the erosion experienced by the alloys is shown to increase with decreasing thermal conductivity and specific heat. The established linear dependence of mass eroded on number of firings suggests that any physical alterations undergone by the eroded surface do not influence future erosion tests. Most significantly, erosion results of the steel alloys (of widely differing compositions) in the ballistic compressor show no distinct difference. The explanation for this lack of dependence on metal composition is the subject of a continuing study. With the exception of the oxygen-containing gases (i.e., air, O_2/N_2 mixtures) and H_2, the mass removal experienced by the steel alloys under the action of N_2, CO, CO_2/A and $N_2/H_2/O_2$ mixtures was very small ($\sim$ 0.25 mg). The erosion of the steel alloy AISI 4340 was found to increase linearly with the mole fraction of O_2 in O_2/N_2 mixtures. The results clearly demonstrate that surface reactions play a dominant role and that erosion is more than simple melting and wipe-off.

Based on work performed under sponsorship of U.S. Army Materials and Mechanics Research Center, Watertown, Mass., under Contract DAAG 46-72-C-0078.

Accession No. AD-A020537 . Available from NTIS.

"EROSION OF METALS BY HIGH PRESSURE COMBUSTION GASES: INERT AND REACTIVE EROSION"

Plett, E. G., Alkidas, A. C., Shrader, R. E., and Summerfield, M.

Journal of Heat Transfer, Vol. 97, pp. 110, 115, 1975.

An experimental and theoretical investigation of the erosion of various metals by high temperature, high pressure flows of combustion gases is described. The erosion process was categorized as either inert or a combination of inert and reactive erosion. Experimental results indicated the existence of two thresholds, the first represents the onset of erosion and the second the transition from purely inert to inert plus reactive erosion. Inert erosion was modeled by means of the melt and wipe-off theory. Experimental results are presented to demonstrate various erosion regimes and to identify the conditions for inert and reactive erosion.

Based on work performed under contract DAAG46-72-C-0078 sponsored by the U.S. Army Materials and Mechanics Research Center, Watertown, Mass., and under contract DAAA-25-71-C0109, sponsored by the U.S. Army Frankford Arsenal, Philadelphia, Pa.

Available from the Engineering Societies Library, New York, N.Y. Abstract 003215, Engineering Index 1975.

"BARREL EROSION PRODUCED BY REACTIVE GASES"

A. C. Alkidas, L. H. Caveny, M. Summerfield and J. W. Johnson

To appear in Proceedings of 1976 JANNAF Propulsion Meeting

An experimental study was conducted to evaluate the thermochemical contributions to the erosion of steel alloys by high pressure and high temperature combustion gases. The erosion of steel alloys is shown to be inversely dependent on thermal conductivity and proportional to the number of firings. Eroded steel surfaces were characterized by the presence of fragmented scale (high carbon to low oxygen content) and by a network of cracks (0.25 to 1.0 μm width) in the underlying metal surface. Crack formations could not be directly related to the mass erosion experienced by the test specimens. Examination of the protective role of wear-reducing additives showed that deposits of additives on the surface provide highly localized chemical isolation and thermal protection from the hot reactive gases. Based on the evidence developed thus far, it is proposed that the primary cause of erosion is the formation of scales (chemical products of gas/steel interactions) which, because of their low adhesive properties, are removed by the aerodynamic forces of the flow.

Based on work performed under sponsorship of the U. S. Army under contract DAAG46-76-C-0069.

"EROSIVE EFFECTS OF HIGH PRESSURE AND HIGH TEMPERATURE PURE GASES ON STEEL"

A. C. Alkidas, C. W. Christoe, L. H. Caveny and M. Summerfield

Accepted for publication in ASME Journal of Engineering Materials and Technology, April 1976.

An experimental study is being conducted to determine the thermochemical mechanisms by which short duration pulses (1 to 2 msec) of high pressure and temperature gases erode steel. A ballistic compressor is used to generate the desired test gas conditions. The erosion of steel by oxygen-containing gases (e.g., air, O_2/N_2 mixtures) was found to be controlled by surface chemical reactions of oxygen. The erosion is linearly proportional to the oxygen mole fraction of the O_2/N_2 mixture. SEM examination of surfaces eroded by air, H_2, and CO showed the formation of scales resulting from gas/surface interactions. It is proposed that, in general, erosion of steel results from the rapid formation of oxides on the surface followed by the removal of the oxides by the aerodynamic forces of the flow.

Based on work performed under sponsorship of the U.S. Army under Contract DAAG46-75-C-0088.

"EROSIVE EFFECTS OF VARIOUS PURE AND COMBUSTION-GENERATED GASES ON METALS, PART II"

A. C. Alkidas, S. O. Morris, C. W. Christoe, L. H. Caveny and M. Summerfield

AMMRC CTR 76- , Army Materials and Mechanics Research Center, Watertown, Mass., July 1976. Also, AMS Report No. 1303, Princeton University, Princeton, N.J.

This study continues the experimental investigation of the thermal and chemical erosion characteristics of steel alloys which were begun under Contract DAAG46-72-C-0078. The high pressure ($\sim$ 3 kbars) and high temperature ($\sim$ 3000 K) environment to which the steel specimens are subjected is produced by a ballistic compressor and by a solid propellant combustor. Equilibrium thermochemical calculations of the possible reactions indicate that the most probable reaction products are oxides, nitrides, carbides, and carbonyls, in that order. The cause of surface cracks was found to be thermal and not relatable to the degree and severity of erosion. Erosion tests of the pure metals used as alloying elements revealed that molybdenum has the highest erosion resistance, followed by nickel. There is no evidence that alloying elements alter the chemical interaction between oxygen and iron. SEM studies revealed that an accumulation of oxide scale occurs with successive firings which provides successively better oxidation protection. It is hypothesized that the primary mechanism of steel erosion under gun barrel conditions is the reaction of the combustion gases with the steel surface to form scale and the subsequent carrying-away of the scale by the high speed flow.

Based on work performed under sponsorship of U.S. Army Materials and Mechanics Research Center, Watertown, Mass., under Contract DAAG46-75-C-0088.

Accession No. AD . Available from NTIS.

"EROSIVE EFFECTS OF HIGH-PRESSURE COMBUSTION GASES ON STEEL ALLOYS"

A. C. Alkidas, S. O. Morris, and M. Summerfield

Journal of Spacecraft and Rockets, Vol. 13, No. 8, August 1976, pp. 461-465.

This study presents an experimental investigation of the thermal and chemical erosion characteristics of steel alloys under the short exposure (2 - 4 msec) of high pressure and high temperature propellant gases. The erosion in short duration tests is shown to be controlled by the chemical interaction of the propellant gases with the surface of the test specimens. The erosion experienced by the steel alloys increases with decreasing thermal conductivity and specific heat. The established linear dependence of mass eroded on number of firings suggests that any physical and chemical alterations undergone by the eroded surface do not influence future erosion tests. Finally, the effects of geometry of the orifice and sulphur addition in the propellant on the erosion of steel alloys were investigated.

Based on work performed under sponsorship of the U.S. Army Materials and Mechanics Research Center, Watertown, Mass., under Contract DAAG46-72-C-0078.

Available from the Engineering Societies Library, New York, N.Y. Abstract 077855, 1976/

"A PERFORMANCE STUDY OF A BALLISTIC COMPRESSOR"

A. C. Alkidas, E. G. Plett, and M. Summerfield

Submitted to AIAA Journal for publication, August 1976.

An experimental and theoretical investigation of the performance of a ballistic compressor is described. Comparison of the computed ideal behavior of the ballistic compressor with experimental test pressures shows that the ideal theory overestimates the generated pressure by as much as 30%. An assessment of the factors responsible for the non-ideal behavior of the ballistic compressor is given. These factors include: valve losses, external and internal (blow-by) leakage, friction of the inertial piston, non-ideal behavior of the driver and test gases, shock wave formations, and heat losses. The valve losses and both the internal and external leakages have been experimentally measured. A parametric study shows that the choice of equation of state of the test gas is not very critical. The heat loss experienced by the test gas was estimated to be 1% of the total energy imparted to the test gas. Shock wave formations have negligible effect on the performance of the ballistic compressor for the mass of the inertial piston (1.34 Kg) used.

Based on work performed under contract DAAG46-72-C-0078 issued by the U.S. Army Materials and Mechanics Research Center, Watertown, Mass.

"HIGH PRESSURE AND HIGH TEMPERATURE GAS-METAL INTERACTIONS"

A. C. Alkidas, L. H. Caveny, M. Summerfield and J. W. Johnson

To appear in Proceedings of 13th JANNAF Combustion Conference September 1976.

Erosion of steel alloys and aluminum alloys by very short exposures ($\sim$ 1 msec) to hot ($\sim$ 3000 K) and high pressure (up to 400 MPa) pure gases (N_2, CO, H_2) and gas mixtures (O_2/N_2, CO/Ar, CO_2/Ar, N_2/H_2O) were characterized. Orifices of the specimen materials were subjected to the test conditions produced by a ballistic compressor. Depending on the test gas, erosion was either produced by simple inert heating or by chemical interaction. As an example of chemical attack, the erosion of both steel and aluminum was linearly proportional to the mole fraction of O_2 in O_2/N_2 mixtures. As an example of inert heating, the higher convective heat transfer rates produced by H_2 produced high erosion rates in both steel and aluminum, while the erosion produced by N_2 was relatively small. In the case of aluminum, the oxidizing gases reacted in the boundary layer to intensify the heat feedback to the surface. In the case of steel, the reactive gases attacked the surface to form oxide layers which were swept away by the high speed flow.

Based on work performed under sponsorship of the U.S. Army under Contract DAAG46-75-C-0088.

"EROSION OF STEEL ALLOYS BY HOT REACTIVE GASES"

A. C. Alkidas, L. H. Caveny, M. Summerfield and J. W. Johnson

To appear in Proceedings of Symposium on Properties of High Temperature Alloys, sponsored by the Electrochemical Society and the Metallurgical Society of AIME, October, 1976.

The erosive action of individual pure gases (N_2, A, CO, H_2) and gas mixtures (O_2/N_2, CO_2/A) at high pressure and high temperature on steel alloys was investigated utilizing a ballistic compressor. Pure H_2 and O_2/H_2 mixtures produced considerably more erosion of the steel alloys than the other test gases. At H_2 molar concentrations of 95% and lower in H_2/N_2 mixtures, the mass erosion experienced by a steel specimen is independent of the H_2 concentration. The erosion of steel was shown to be linearly proportional to the mole fraction of O_2 in O_2/N_2 mixtures. Repetitive tests indicated that erosion decreased with the number of firings; this demonstrates that the oxide scale produced by the iron/oxygen interaction is not totally removed by the flow and, therefore, oxide accumulation occurs, providing successively better oxidation protection. Based on SEM studies, it is hypothesized that erosion results from the formation of the scale by chemical interaction and the subsequent removal of the scale by the high velocity gases.

Based on work performed under sponsorship of U.S. Army Materials and Mechanics Research Center, Watertown, Mass., under Contract DAAG46-72-C-0078.

VII COMBUSTION NOISE

VII COMBUSTION NOISE

VII COMBUSTION NOISE

VII COMBUSTION NOISE

"NOISE OF JETS DISCHARGING FROM A DUCT CONTAINING BLUFF BODIES."

E. G. Plett, T. M. Tower, A. N. Abdelhamid and M. Summerfield

Proceedings of INTER-NOISE 72, International Conference on Noise Control Engineering, October 1972; Institute of Noise Control Engineering, pp.477-481.

Results of experiments in which noise originating from a ducted flow, exhausting as a jet into an anechoic chamber with and without bluff bodies inside the duct, are presented. Directivity patterns indicate a stronger lateral dipole in the horizontal far field when the internal strut is vertical than when it is horizontal. The overall noise observed in the horizontal plane is much more intense for the case with the vertical strut than with the horizontal strut, indicating that the fluctuating lift on the strut contributes more noise than the fluctuating drag, at flow rates producing aeolian tones above the (1,0) mode cut-off in the duct. Crosscorrelations to verify that the dominant noise originated inside the duct are presented.

Based on work performed under contract N00014-67-A-0151-0029 issued by the Power Branch of the Office of Naval Research.

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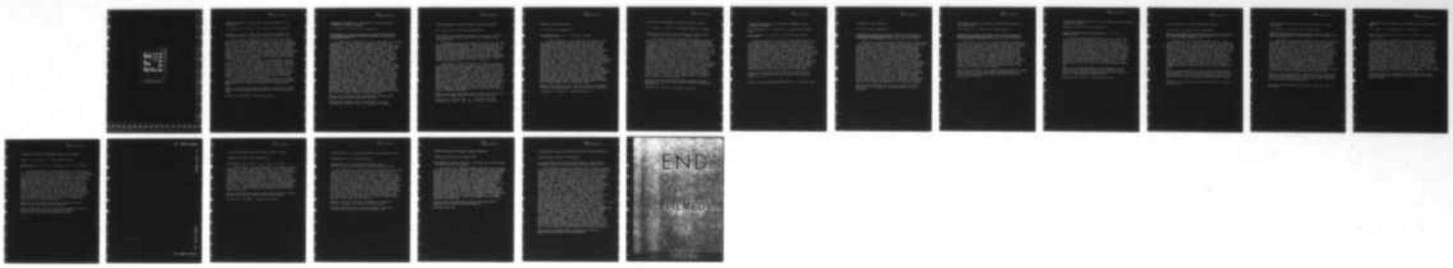

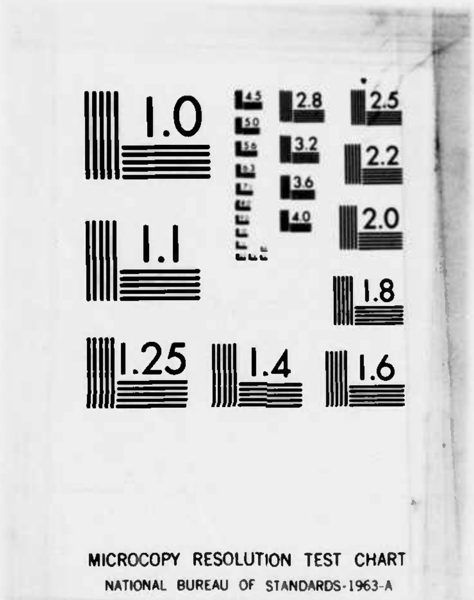
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"NOISE GENERATION BY CYLINDRICAL SPOILERS IMMERSED IN AN AIR DUCT."

T. M. Tower, E. G. Plett, H. H. Chiu, and M. Summerfield

AMS Report No. 1092, March 1973, Aerospace and Mechanical Sciences Department, Princeton University, Princeton, N.J.

This study is concerned with the effect of thin cylindrical flow spoilers upstream of the exit plane of a constant-area duct on the acoustic power output and directivity patterns of the noise field external to the duct. Spoilers of diameter 1/16", 5/32", and 3/16" were placed at 1/8" and 11" from the exit plane of a 1" diameter duct. Far-field sound pressure levels were measured in an anechoic chamber over a mean velocity range of 250 to 900 ft/s. The frequency range of the investigation was 200 Hz to 50 kHz, while the Reynolds number range, based on mean velocity upstream of the spoiler and on spoiler diameter, was 0.8×10^4 to 10^5.

A cylindrical spoiler placed 10 duct diameters from the duct exit plane caused the acoustic power output to increase by between 5 and 30 dB, a large part of the increase occurring at the (1,0) duct cut-off frequency due to excitation of the (1,0) mode by the lift fluctuations at the spoiler. The acoustic power of the spoilers was found not to obey the U^6 dipole law; instead, the velocity exponent was found to depend largely on the variation in lift coefficient with Reynolds number. The directivity patterns of the spoiler-generated noise were found to be non-axisymmetric.

An attempt was made to theoretically predict the acoustic power output of the spoilers at 1/8" from the duct exit plane. Agreement between theory and experiment was qualitatively good.

Based on work performed under sponsorship of the Power Branch, Office of Naval Research under contract No. N00014-67-A-0151-0029.

Accession No. AD767336. Available from NTIS.

"COMBUSTION ROUGHNESS AS A CONTRIBUTION TO THE JET NOISE COMPONENT OF AIRCRAFT ENGINES"

E. G. Plett, H. H. Chiu and M. Summerfield

Proceedings of Interagency Symposium on University Research in Transportation Noise, Stanford University, Stanford, CA, March 28-30, 1973.

An experimental demonstration of the importance of unsteady combustion as a noise source in aircraft jet engines was undertaken. Internal pressure fluctuations and far field noise measurements on a combustion chamber/jet nozzle configuration have been obtained for jet Mach numbers between 0.2 and 0.35 (exhaust gas temperature 1600° to 2200° R). The dominant combustion frequencies observed inside the combustor can be altered by altering air-fuel ratio, air flow rate, and flame holder geometry; a strong unalterable component is always present corresponding to an organ pipe oscillation. Farfield microphones show the same dominant combustion frequencies, including the organ-pipe frequency. A fluid mechanical-acoustical analysis shows that ultra-low frequencies of flow oscillations are less efficient noise sources than their higher harmonics. This is verified in experiments where the harmonics are stronger, relative to the fundamental, in the far field than in the combustor. Overall noise levels are about 15 dB above levels at the same flow Mach number, without combustion, and 30 dB above clean-jet (cold) noise, at the same Mach number, while the directivity pattern is almost circular, unlike jet shear joise. Strong cross-correlations between internal unsteadiness and external noise is found. A fluid mechanical simple source model is used to predict the noise levels expected, and is found to give good agreement with experiments. Future work will be aimed at exploring the same phenomena at higher subsonic and supersonic jet speeds and at characterizing the unsteady combustion and unsteady exit plane flow in more complete terms for model analysis.

Based on work performed under sponsorship of NASA-Langley Research Center under Grant NGR 31-001-241.

Accession No. AD781174 (Vol.I). Available from NTIS.
Accession No. AD781175 (Vol. II). Available from NTIS.

"NOISE GENERATED BY DUCTED AIR-FUEL COMBUSTION SYSTEMS"

E. G. Plett, H. H. Chiu and M. Summerfield

Proceedings of Interagency Symposium on University Research in Transportation Noise, March 1973, U.S. Department of Transportation.

An analysis, using a gas dynamic formulation to describe the turbulent flame structure, reveals two mechanisms of noise generation by combustion. The frequencies and the amplitude of the noise field generated by the turbulent fluctuation are primarily determined by the quasi-steady flame structure and the fluctuation in the rate of heat release induced by temperature and velocity fluctuations. Self-sustained non-linear oscillations could result from fluctuations in the rate of heat release caused by fluctuation in rate sensitive properties (T' , Y', ρ' , etc.).

Experiments to study the effect of a confining duct on a noise source region, and to study the parameters governing the propagation of noise generated inside the duct to a far-field point, are being conducted. Cylindrical struts ranging from 0.10 to 0.187" diameter are placed across a 1" diameter duct at several axial locations, and the far-field noise is compared with that of a clean, free jet operating between 250 and 1000 ft/sec. For example, the strut placed at the exit plane of the nozzle produces noise levels which exceed the jet noise power by about 10 dB, whereas the same strut located internally 11" upstream of the exit plane produces a further increase of 5 to 20 dB sound power. Clearly, a confining duct strongly influences the nature of a noise source and must be included when combustion noise contributions from jet engines are being estimated.

Based on work performed under contract N00014-67-A-0151-0029 issued by the Power Branch, Office of Naval Research.

Accession No. AD781174 (Vol. I). Available from NTIS.
Accession No. AD781175 (Vol. II). Available from NTIS.

"THEORY OF COMBUSTION NOISE"

H. H. Chiu and M. Summerfield

Acta Astronautica, Vol. 1, 1974, pp. 967-984.

A unified theory of noise generation and amplification by turbulent combustion of premixed fuel and liquid fuel droplets, has been developed within the framework of the fluid mechanics of the reacting gas. The overall sound generation processes have been classified in terms of the sound due to an isolated turbulent flame and that due to the interaction of a flame with its environment in a typical combustor. The analysis has been focused on, (i) the far field noise characteristics, and (ii) the mechanism of sound generation, dispersion, and transmission in the vicinity of an open flame. The acoustic intensity generated by a turbulent premixed flame is found to be a function of the relevant aero-thermochemical parameters and the flame structural factor, expressed in terms of six double correlation functions characterizing the flame structure. Explicit expressions for the sound intensities are obtained based on a wrinkled flame model and a distributed reaction model. Noise generated by liquid droplets are classified in terms of intrinsic and turbulent driven noise components. Analysis of ducted combustion systems reveals that resonant oscillations occur with resulting noise intensities far greater than from the corresponding open flame. Calculated sound intensity spectra are in good agreement with experimental data.

Based on work performed under contract N00014-67-A-0151-0029 issued by the Power Branch of the Office of Naval Research.

Accession No. AD-A001108. Available from NTIS.

BLAST-NOISE ENVIRONMENT OF IMPULSIVE ROCKET FIRINGS.

H. H. Chiu, E. G. Plett, M. Summerfield and C. W. Nelson.

AIAA Paper No. 74-48, American Institute of Aeronautics and Astronautics, New York, N.Y., January 1974.

An analysis to obtain pressure-time predictions in the vicinity of the impulsively growing, underexpanded exhaust flow from a rocket motor is presented. A generalized model treating the exhaust as a spherically expanding plume, using an assumed power law density distribution as well as an asymptotic expansion to obtain the blast wave solution in the region surrounding the plume is one method of attack on the problem; a two-dimensional inviscid numerical solution of the internal and external flow fields is a second method; an axisymmetric numerical solution of the blast surrounding a cylindrically expanding jet volume is a third method used. A transient wave structure is observed in each case, the nature of which is determined by the variation of jet surface velocity during the growth and decay of the jet. The pressure peak is observed to progress outward, forming a shock front, and in some cases an N-wave is formed in the pressure profile after some time, with profiles similar to those observed in experiments. While each of the models lacks certain features of a real jet, each results in predicted trends which, it is hoped, will suggest ways of reducing the severity of the blast field.

Based on work performed under Contract DAAD05-73-C-0502 sponsored by the U.S. Army, Ballistic Research Laboratories, Aberdeen, Md.

Accession No. A74-20757. Available from AIAA.

"NOISE CHARACTERISTICS OF COMBUSTION AUGMENTED JETS AT MIDSUBSONIC SPEEDS"

A. N. Abdelhamid, D. T. Harrje, E. G. Plett and M. Summerfield

AIAA Journal, Vol. 12, No. 3, March 1974, pp. 336-342.

Noise generation by a subsonic flow discharging from a combustion chamber is examined with regard to the relative importance of combustion as a source of noise in such a flow system. Measurements of pressure fluctuations inside the combustor are compared with far field noise measurements by direct crosscorrelations. The crosscorrelations and derived cross-spectral densities verify that much of the noise originates inside the combustor. A first order fluid mechanic perturbation model is used to predict exit plane velocity fluctuations due to internal pressure fluctuations. This unsteadiness at the exit plane is assumed to behave as an acoustic monopole which radiates to the far field. Far field noise levels estimated on this basis are in good agreement with measured values. The overall noise level from the combustor/jet is found to be 10 to 20 dB higher than for an equivalent clean, cold jet at the same exit velocity.

Based on work performed under NASA Grant NGR 31-001-241 issued by the Acoustics Branch of NASA Langley Research Center.

Journal Article supersedes AIAA Paper No. 73-189, Jan. 1973.

"COMBUSTION NOISE THEORY."

H. H. Chiu and M. Summerfield

Proceedings of Second Interagency Symposium on University Research in Transportation Noise, Vol. II, North Carolina State University, Raleigh, N.C., June 1974, pp. 733-747.

Mechanisms of sound generation, amplification and scattering by various combustion systems are described on theoretical bases compatible with the contemporary understanding of unsteady burning processes. Sound generation mechanisms are classified into categories relating to the Smith-Kilham emission mechanism and the turbulent driven Rijke-Riess emission mechanism. The intensity of the generated sound is found to be proportional to the combustion sound number and the flame structural factor which depend on detailed structure of a flame. Experimental correlation of the intensities of the sound emitted and the light radiated from free radicals is also discussed. Analytical and experimental investigations revealed that the noise generation by ducted burners depends on the nature of the rough burning and the duct resonance which is identified as the source of the observed multiple peak structure in sound spectra. Interactions within the flow through the combustor-turbomachinery components within a gas turbine are predicted to produce similar multiple peak noise spectra. Scattering of the plane sound wave by a flame is also discussed. Quantitative correlations between the intensity of the scattered sound wave and the physical parameters of the flame are obtained.

Based on work performed under contract N00014-67-A-0151-0029 issued by the Power Branch of the Office of Naval Research.

"COMBUSTOR GEOMETRY AND COMBUSTION ROUGHNESS RELATION TO NOISE GENERATION,"

E. G. Plett, M. D. Leshner and M. Summerfield

Proceedings of Second Interagency Symposium on University Research in Transportation Noise, Vol. II, North Carolina State University, Raleigh, N.C., June 1974, pp. 723-732.

Some results of a study of the importance of geometrical features of the combustor to combustion roughness and resulting noise are presented. Comparison is made among a perforated can flame holder, a plane slotted flame holder and a plane slotted flame holder which introduces two counter swirling streams. The latter is found to permit the most stable, quiet combustion. Crosscorrelations between the time derivative of chamber pressure fluctuations and far field noise are found to be stronger than between the far field noise and the direct chamber pressure signal. Temperature fluctuations in the combustor nozzle are also found to have a reasonably strong crosscorrelation with far field sound. Indications are given of areas where further work is planned relating to these findings.

Based on work performed under NASA Grants NGR31-001-241 issued by the Acoustics Division of Langley Research Center and NGR31-001-307 issued by the V/STOL and Noise Division of Lewis Research Center.

"JET ENGINE EXHAUST NOISE DUE TO ROUGH COMBUSTION AND NONSTEADY AERODYNAMIC SOURCES"

Edelbert G. Plett and Martin Summerfield

Journal of Acoustical Soc. of America, Vol. 56, No. 2, August, 1974.

Internal sources are accounted for in terms of fluctuations in mass and momentum at the nozzle exit plane. Detailed laboratory scale data are used in conjunction with the analysis to determine effective scaling parameters linking physically measurable quantities to the mathematical model used. The resulting model is used to predict contributions from various sources in a typical jet engine exhaust. Mass-flow fluctuations generated at the exit plane by combustion-driven acoustic-resonant-type fluctuations inside the engine are found to be dominant up to jet Mach numbers around 0.45, after which mass-flow fluctuations at nozzle-dominated frequencies become most dominant. The jet contribution, or exit plane momentum fluctuations, are not found significant below Mach 1, for the conditions considered.

Based on work performed under contract N00014-67-A-0151-0029 issued by the Power Branch of the Office of Naval Research and Grant NGR 31-001-241 issued by the Acoustics Branch of NASA-Langley Research Center.

Accession No. A74-41413. Available from AIAA.

"NOISE GENERATION BY DUCTED COMBUSTION SYSTEMS"

H. H. Chiu, E. G. Plett and M. Summerfield

Progress in Astronautics and Aeronautics; Aeroacoustics: Jet Noise and Combustion Noise; Duct Acoustics, Vol. 27, 1975 pp. 249-276, AIAA, New York, N.Y.

Analysis of the interaction between a zone of non-steady combustion and its confining duct shows that resonant type oscillations occur with resulting noise intensities far greater than from corresponding unconfined flame zones. The blading action on the flow through the compressor and turbine of an engine generates discrete frequency noise which, it is found, is enhanced by the response of the combustion zone in between. Ducted combustor experiments verify the predicted resonant type noise, the amplitude and frequency of which are strongly influenced by the duct dimensions and end impedance. A convergent exit nozzle results in stronger internal resonant noise oscillations but also generates a higher jet velocity, with the attendant jet noise which exceeds noise from inside the duct at jet Mach numbers near unity.

Based on work performed in part under ONR Contract N00014-67-A-0151-0029, issued by the Power Branch of the Office of Naval Research, and in part under NASA Grant NGR31-001-241, issued by the Acoustics Branch of Langley Research Center.

The above cited article supersedes AIAA Paper No. 73-1024, October 1973.

"COMBUSTION INTENSITY AND DISTRIBUTION RELATION TO NOISE GENERATION."

E. G. Plett, M. D. Leshner and M. Summerfield

Progress in Astronautics and Aeronautics, Aeroacoustics: Jet Noise, Combustion and Core Engine Noise, Vol. 43, 1976, AIAA, New York, N.Y.

Experiments with several different flame holder geometries were conducted to investigate the degree to which combustion roughness can be altered by altering the flame intensity and flame distribution in a ducted combustion system. The effect of admitting primary air through a plane-slotted or a slotted-swirl vane flame holder was compared and the combustion roughness and noise was contrasted with that obtained with a closed front-end perforated can. The slotted front-end burners produced much smoother burning and less noise than the closed front-end can. No advantage was apparent with swirl vs non-swirl when approximately the same inlet flow distribution was maintained. Preheated inlet air provided somewhat smoother combustion as compared with ambient temperature air. The combustion roughness with methyl alcohol was briefly compared with that of iso-octane; indications are that it burns more smoothly, but more detailed studies are needed to substantiate these indications.

Based on work performed under Contract N00014-67-A-0151-0029 issued by the Power Branch of the Office of Naval Research and NASA Grant NGR31-001-307 issued by the V/STOL and Noise Division of Lewis Research Center.

The above cited article supersedes AIAA Paper No. 75-524, March 1975.

"COMBUSTION NOISE ALTERATION IN TORCHES BY MEANS OF PERTURBING RODS"

E. G. Plett, M. D. Leshner and M. Summerfield

Submitted to Journal of the Acoustical Society of America, June 2, 1976.

Alteration of combustion noise from propane and oxygen-acetylene torches resulting from insertion of transverse and longitudinal perturbing rods is reported. The noise from propane torches is reduced by 8 - 10 dB in the mid-frequency range between 700 and 3000 Hz as a result of inserting 6 rods across the induction nozzle of the supply tube. It was noted that the rods inhibited the influx of air; a similar flow reduction ($\sim$ 30%) by a simpler means resulted in even greater noise reduction, suggesting that the use of transverse rods, in this configuration, was not the best means of reducing combustion noise. A single longitudinal rod inserted through the supply tube and into the flame zone of an oxygen-acetylene torch was observed to disturb the flame shape, alter the azimuthal symmetry of the sound pressure level contours and increase the high frequency noise (above $\sim$ 10 kHz) of the flame without altering the flow rate of combustibles. In some cases, modest reductions (< 3 dB) of noise were observed.

Work performed under sponsorship of NASA-Lewis Grant NGR31-001-307 issued by the V/STOL and Noise Division of Lewis Research Center.

"OPTICAL EVALUATION OF COMBUSTION NOISE SOURCE TERMS"

Shafer, H. J., Plett, E. G., and Summerfield, M.

AIAA Journal, Vol. 14, No. 9, September 1976, pp. 1163-1164.

The physicochemical processes believed to be responsible for noise generation in turbulent combustion have been described in terms of several alternate analytical models. Strahle adopted the Lighthill-type wave operator formulation to obtain semi-empirical expressions for acoustic power based on the wrinkled flame model and the distributed reaction model. Chiu and Summerfield adopted the convected wave equation approach and employed the method of multizones to account for nonhomogeneities and source convection within the flame zone. This latter theory, as a result of its less restrictive approach, contains several source terms not found in the Strahle theory. In the work described herein, measurements have been made to compare the magnitude of one of the additional terms found in the Chiu-Summerfield theory with that of the term found in Strahle theory. It is found that they are of comparable intensity for some flame conditions.

Based on work performed under Contract N00014-75-C-0507 sponsored by the Office of Naval Research.

Presented as Paper 76-38 at the AIAA 14th Aerospace Sciences Meeting; full paper available from AIAA Library. Accession No. A76-18751. Available from AIAA.

VIII DROPLET BURNING

VIII DROPLET BURNING

VIII DROPLET BURNING

VIII DROPLET BURNING

"ON THE QUASI-STEADY ASSUMPTIONS FOR A BURNING DROPLET."

Josette Bellan and Martin Summerfield

AIAA Journal, Vol. 14, No. 7, July 1976, pp. 973-975.

A large number of results obtained in the field of droplet combustion are based upon the assumption that the gas field behaves in a quasi-steady manner. However, this assumption is introduced usually without adequate justification. Therefore, it is felt here that the discussion on the possibility of realistically making the quasi-steady assumption for the gas phase deserves particular attention. It was shown that for droplets in the range encountered in Diesel engines or rockets, there is a domain in the plane (τ_p, p) (τ_p is a characteristic time and p is a pressure) where the quasi-steady assumption is valid for typical pressures developed in the above combustion systems. As the droplet size decreases, the domain is shown to be larger.

Based on work performed under Contract N00014-75-C-0705 issued by the Power Branch of the Office of Naval Research.

Accession No. A76-39441. Available from AIAA.

"COMPARISON OF FOUR MODELS DESCRIBING COMBUSTION OF DROPLETS"

Josette Bellan and Martin Summerfield

Presented at the 1976 Technical Meeting of the
Eastern Section, The Combustion Institute, November 1976

The comparison is made between a formulation using a finite reaction rate and three other formulations based upon the flame-sheet approximation. The difference among these latter models consists in the treatment of the evaporation from the surface and also of the molecular weights. The theory is valid for steady or unsteady burning of droplets. Numerical results for decane show that the thin flame approximation is excellent at 10 atm but unacceptable at 1 atm. Among the flame-sheet models, the one using nonequilibrium evaporation and individual molecular weights approximates best the finite reaction rate theory. This good agreement breaks down in more-oxidant-than-air ambient atmospheres. The Clausius-Clapeyron approximation is shown to be excellent at 10 atm and still good at 1 atm. When averaging the molecular weights large underestimates of the evaporation rate are obtained. The thermal layer of the droplet is also greatly misestimated.

Based on work performed under sponsorship of the Office of Naval Research under Contract N00014-75-C-0705.

Available through your local library system and/or from the Engineering Societies Library, New York, N.Y.

A MODEL FOR STUDYING UNSTEADY DROPLET COMBUSTION

Josette Bellan and Martin Summerfield

AIAA Paper No. 76-614, July 1976. New York: American Institute of Aeronautics and Astronautics.

The concept of a reduced boundary condition at the surface of a droplet is used to develop a new theory of unsteady droplet burning. This theory utilizes a quasi-steady gas phase assumption which has been shown to be realistic for a wide range of droplet sizes at low pressures. The most significant consequence of the theory is that the problem of unsteady droplet burning is reduced to the solving of a single diffusion-type nonlinear partial differential equation having one of its boundary conditions determined by an algebraic function of the quasi-steady gas phase variables. This reduced boundary condition incorporates the entire dependence of the solution on fuel characteristics, chemical kinetics and thermal properties of the gases. An experiment is proposed for determining this boundary condition so that the nonsteady droplet combustion problem can be solved for a realistic situation. By using additional assumptions, a numerical estimate of the boundary condition has been made.

Based on work performed under contract N00014-75-C-0705 sponsored by the Office of Naval Research.

Available from AIAA.

A THEORETICAL STUDY OF DROPLET EXTINCTION BY DEPRESSURIZATION

Josette Bellan and Martin Summerfield

To be presented at the 1977 Spring Technical Meeting of the Combustion Institute, Central States Section, March, 1977

The combustion behavior of droplets under transient ambient conditions directly influences both the power and pollutant output of many power systems. The particular conditions at which droplet extinction occurs are of interest since the time required to reach them can strongly affect the pollutant production. In fact, if these conditions are known, the extinction time could conceivably be tailored to maximize the power: pollutant ratio. In this work droplet extinction is demonstrated using a recently proposed description of droplet combustion under diverse conditions. Both regressing and constant size droplets are studied. In absence of depressurization ($p = 10$ atm): (1) a constant-size droplet of radius 10^{-2} cm does not extinguish, and (2) a regressing droplet with an initial radius of 10^{-2} cm does not extinguish in 6.25 ms (the radius will have to decrease much further for the droplet to meet the extinction condition). As depressurization is imposed, both types of droplets extinguish. The extinction time as well as the extinction pressure are shown to be decreasing functions of the e-folding of the depressurization rate. Also, regressing droplets extinguish faster than constant-size droplets exposed to the same depressurization. Extinction boundaries are built as functions of the initial temperature profile in the droplet (uniform and nonuniform), the initial pressure, and the droplet thermal diffusivity. The effect of the kinetics is studied as well. This study shows that (1) in contrast to constant-size droplets, the extinction boundaries for regressing droplets are only weak functions of the initial temperature, (2) extinction becomes easier with decreasing initial pressure for both types of droplets, (3) the droplet thermal diffusivity has no significant effect upon extinction (if the initial temperature profile is the same), and (4) the kinetics is very important in determing extinction.

Based on work performed under Contract N00014-75-C0705 sponsored by the Office of Naval Research.

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